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ARTIFICIAL GRAVITY EXPERIMENT

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MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
JANUARY 1968

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STATUS REPORT

ARTIFICIAL GRAVITY EXPERIMENT

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Prepared by: Allen J. Louviere

and

Maynard C. Dalton

Approved By: W. E. Stoney, Jr.
Chief, Advanced Spacecraft
Technology Division

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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A C K N O W L E D G E M E N T

This document is the result of the combined efforts of the Flight Operations, Medical, and Engineering and Development Directorates of the Manned Spacecraft Center. Systems, technical analyses, human factors and medical data inputs were integrated by the Advanced Spacecraft Technology Division. The effort required major technical support, which is evidenced by the rather lengthy list of contributors. However, specific recognition is given to Mr. Maynard Dalton who, in part or totally, authored, compiled, integrated, and edited the final documentation, in addition to his configuration contributions. Likewise, Dr. R. Downs' contributions in the Moby Dick concepts were invaluable.

The resulting document is thought to be an excellent, technical cooperative effort. The major contributors are listed as follows:

Medical Research and Operations Directorate:	R. E. Waite
Flight Operations Directorate:	R. E. French
Engineering & Development Directorate:	
Crew Systems Division:	Dr. W. E. Feddersen J. T. Jackson J. Reed M. Radnofsky
Instrumentation & Electronic Sys. Div.:	C. D. Levy M. Engert W. E. Mallary R. Humer S. Lenett J. Fowler D. Eggers M. D. Blackman D. Cubley J. Kelly R, M. Dickerson D. R. Smith W. F. Ritz G. Wenzel
Guidance & Control Division:	G. Xenakis C. Lively L. Tilton F. Elam J. Sunkel E. Simon

Structures & Mechanics Division:	Dr. R. Downs D. Greenshields
Propulsion & Power Division:	C. Glassburn D. Hydrick D. Murrell
Advanced Spacecraft Technology Division:	M. Dalton C. Schneider L. Livingston G. Murphree C. Beers R. Bazhaw J. Fitzgerald W. Taub G. Chisholm, Jr. H. Mandell, Jr. E. Phelps D. Hall A. Louviere T. Wall A. Hoffpauir I. Short

SUMMARY

An investigation into the desirability and the practicality of an artificial gravity experiment, within the limits of the AAP program, is presented in this report. It was determined that such an experiment not only could be flown, but, indeed should be flown to provide comparative artificial and zero gravity data.

Three artificial gravity station concepts were developed and evaluated as to cost, operational safety, and capability. Two of the concepts were eliminated on the basis of operational safety and other considerations.

The preferred concept, the cable-connected vehicle - light weight enough to be launched with a single S-IB booster; long enough to provide 0.3 "g" at 3.4 rpm, large enough to house two crewmen and the required bio-medical experiments, adaptable enough to provide variable gravity, simple enough to fly without extensive development, inexpensive enough to fit the AAP budget, and timely enough to provide answers concerning artificial gravity early in the space program - was developed in sufficient depth to indicate the direction for further study and design efforts.

INTRODUCTION

As the exploration of space advances further into the unknown, numerous questions concerning man's physical participation in the program continually arise. One main problem seems to be his adaptability to the new environment.

It is possible that man cannot physically adapt to a long-term, zero gravity environment, since zero gravity requires startlingly different techniques for every aspect of man's existance. His earth-developed methods of locomotion are neither valid nor useable, and even his internal organs may become disoriented. Medical reports delineate certain physical changes in the bodies of some of the astronauts after their relatively short-duration missions and the available data do not indicate whether these changes will increase, decrease or continue unchanged for long-duration space flight.

It is also entirely possible that, although zero gravity may prove to be acceptable, it may not be desirable for long-term space flight. Zero gravity is required for most of the envisioned experiments and sensors; however, the crew tasks which support these experiments can be accomplished more easily in artificial gravity. Such tasks as sleeping, eating, and systems and station housekeeping can be performed much more efficiently in a gravity environment. Since these require from 60 to 75 percent of the total time in space, artificial gravity may be highly desirable.

Since a zero gravity environment may be neither acceptable nor desirable, it would seem logical that some comparative study with artificial gravity should be instituted reasonably early in the space program. This report presents reasons why such a study should be undertaken and provides a preliminary concept of how it could be accomplished.

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Conclusions

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1.0 COST EFFECTIVENESS

It is not unreasonable to assume that the results of a manned space flight are directly dependent on man's work performance. On this basis, total mission cost divided by the total amount of useful work performed by the crew can be used as a measure of cost effectiveness to compare artificial gravity with zero gravity.

1.1 TASK PERFORMANCE EFFICIENCY

The first step in such an evaluation is to establish the relationship between gravity level and work performance. Figure 1.1 has been projected from Lockheed test data at 1/6 g and qualitative results of aircraft partial gravity flights. Efficiency is measured in terms of work done per unit of time relative to a normal gravity environment. The curve which represents performance under low gravity levels with suitable restraints is based on an interpretation of an AiResearch Study. Although available data are insufficient for precise definition, the curves are believed to be reasonably correct.

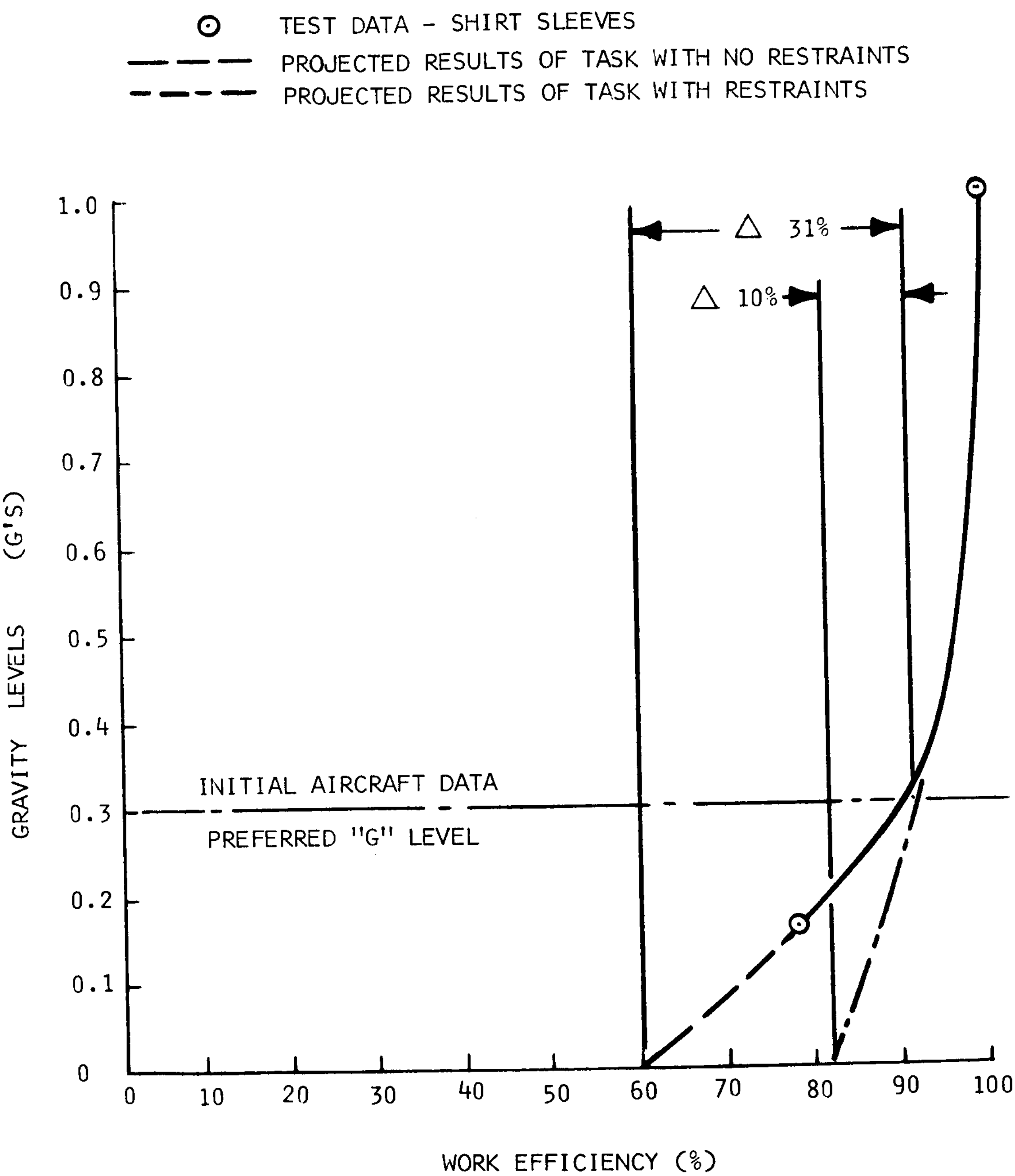
From partial gravity aircraft experiments, 0.3 g appears to be the lowest gravity level at which task performance (torquing bolts, pouring water, etc.) approximates normal gravity. An increase to 0.5 g results in very little improvement. Therefore, 0.3 g has been taken as the preferred level for the purposes of this study.

1.2 AVAILABLE WORK TIME

Based on these projected efficiencies and a typical daily activity schedule, the amount of "useful" work done (other than personal and housekeeping tasks) can be estimated as a function of gravity level. This is illustrated in Figure 1.2 for three conditions: zero gravity unrestrained, zero gravity restrained, and 0.3 g artificial gravity. The time required for all activities except sleeping, eating, and exercise has been adjusted according to the efficiencies of Figure 1.1. Exercise for artificial gravity has been reduced to reflect deletion of pressure cuffs, etc., required for conditioning in zero gravity.

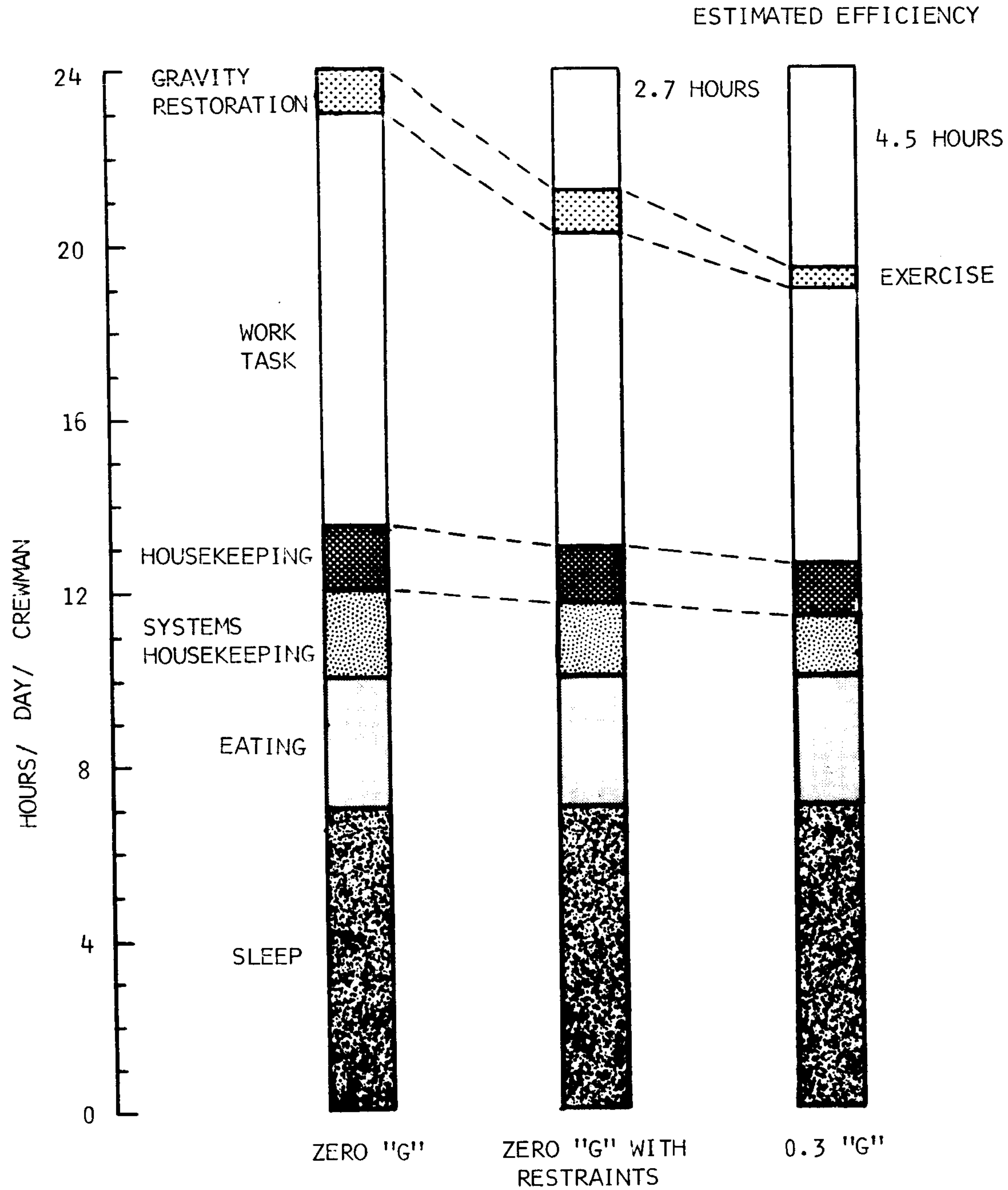
1.3 PRODUCTIVE WORK COST COMPARISON

The time allotments of Section 1.2 can be described for purposes of analysis as follows. Let W represent time available for experimentation in terms of 1 g equivalent man-hours/man-day and e represent relative task performance efficiency from Section 1.1. Using subscripts O, R, and G for zero gravity unrestrained, zero gravity restrained, and artificial gravity, respectively,



ESTIMATED WORK EFFICIENCY IMPROVEMENT VS. GRAVITY LEVEL

FIGURE 1.1



ESTIMATED EFFECTS OF "G" LEVELS ON WORK EFFICIENCY

FIGURE 1.2

$$W_O = 9.5e_O$$

$$W_R = (13 - 3.5\ e_O/e_R)e_R$$

$$= 13\ e_R - 3.5e_O$$

$$W_G = (13.5 - 3.5\ e_O/e_G)e_G$$

$$= 13.5\ e_G - 3.5\ e_O$$

If C = cost per useful man-hour, M = total mission cost, ΔM = additional cost of artificial gravity per mission, S = crew size, and D = mission duration, then

$$C_R = \frac{M}{SDW_R}$$

$$= \frac{M}{SD(13\ e_R - 3.5\ e_O)}$$

$$C_G = \frac{M + \Delta M}{SDW_G}$$

$$= \frac{M = \Delta M}{SD(13.5\ e_G - 3.5\ e_O)}$$

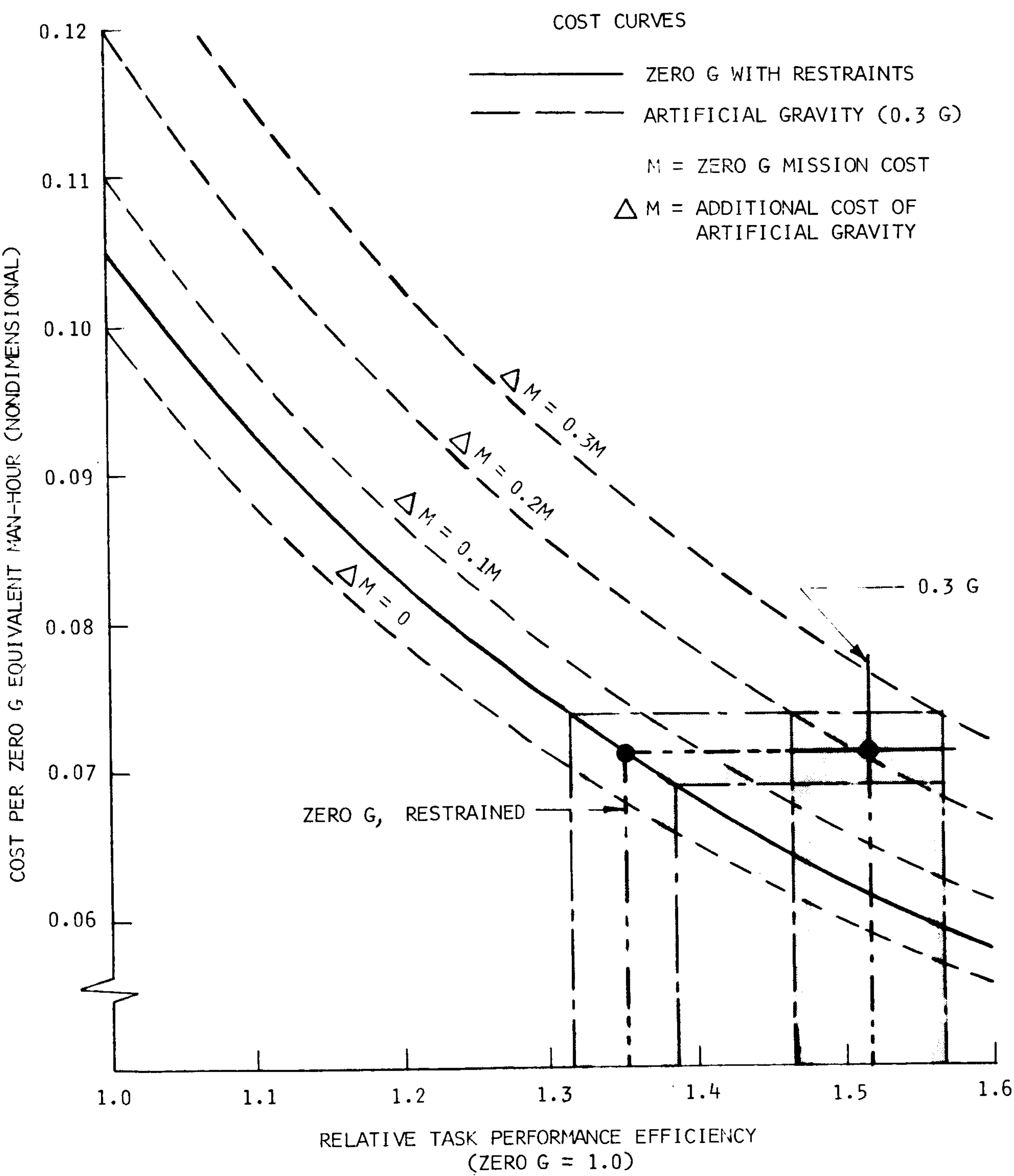
To avoid considering specific cases, the above equations may be nondimensionalized:

$$C_R \frac{SDe_O}{M} = \frac{1}{13\ e_R/e_O - 3.5}$$

$$C_G \frac{SDe_O}{M} = \frac{1 + \Delta M/M}{13.5\ e_G/e_O - 3.5}$$

These equations are plotted in Figure 1.3. The abscissa is e_R/e_O or e_G/e_O as appropriate and the ordinate is $CSDe_O/M$. A family of curves represents various values of $\Delta M/M$. The derived equations are such that zero gravity becomes the basis for comparison. However, since only relative values are of interest here, the basis is immaterial.

Using efficiencies from Section 1.1, the nondimensional cost per man-hour is 0.071 for zero gravity operation with restraints. Proceeding horizontally to the artificial gravity efficiency line, it is seen that if artificial gravity adds 21% to the total mission cost, the cost per unit of useful work done is the same as for zero gravity.



ARTIFICIAL GRAVITY COST EFFECTIVENESS

FIGURE 1.3

Since the accuracy of the values used is questionable, bands representing variations of plus or minus 10% are shown to indicate the sensitivity of $\Delta M/M$ to efficiency.

The additional costs that would result from incorporation of artificial gravity have not been investigated. It is unlikely that such costs will exceed the break-even point indicated by Figure 1.3 for a completely new spacecraft, although it is possible in the event that artificial gravity is added to an existing spacecraft.

2.0 PROGRAM PLANNING

2.1 EXISTING PLANNING

The existing concept for earth-orbit, manned space experimentation is the AAP program. This program envisions a step-by-step explorative process starting with a small station and culminating in a large zero gravity station. Many experiments will be accomplished, but, no comparison with artificial gravity will be made. This, of course, is logical, since the planned configurations were designed to meet the zero "g" requirements for the sensors and experiments.

However, since it is not at all certain that long-term zero gravity is acceptable to man, it would seem that his requirements should also be considered. Particularly so, since from 60 to 75 percent of his time in space is spent on tasks that can be accomplished much more efficiently in a gravity environment.

2.2 ALTERNATE PLAN

An alternate plan should provide an artificial gravity experiment reasonably early in the program. If such an experiment was launched on the first AAP flight subsequent to the cluster flight, it would provide a timely comparison with zero gravity. If the results of such a comparison were favorable, the follow-on experimentation could incorporate both zero and artificial gravity features as required.

Figure 2.1 is a graphic representation of how a follow-on program could be planned. This plan recognizes that the economic aspects of artificial gravity may well be the overriding factor in the continuation of such a plan. The main comparison parameters are indicated on the figure.

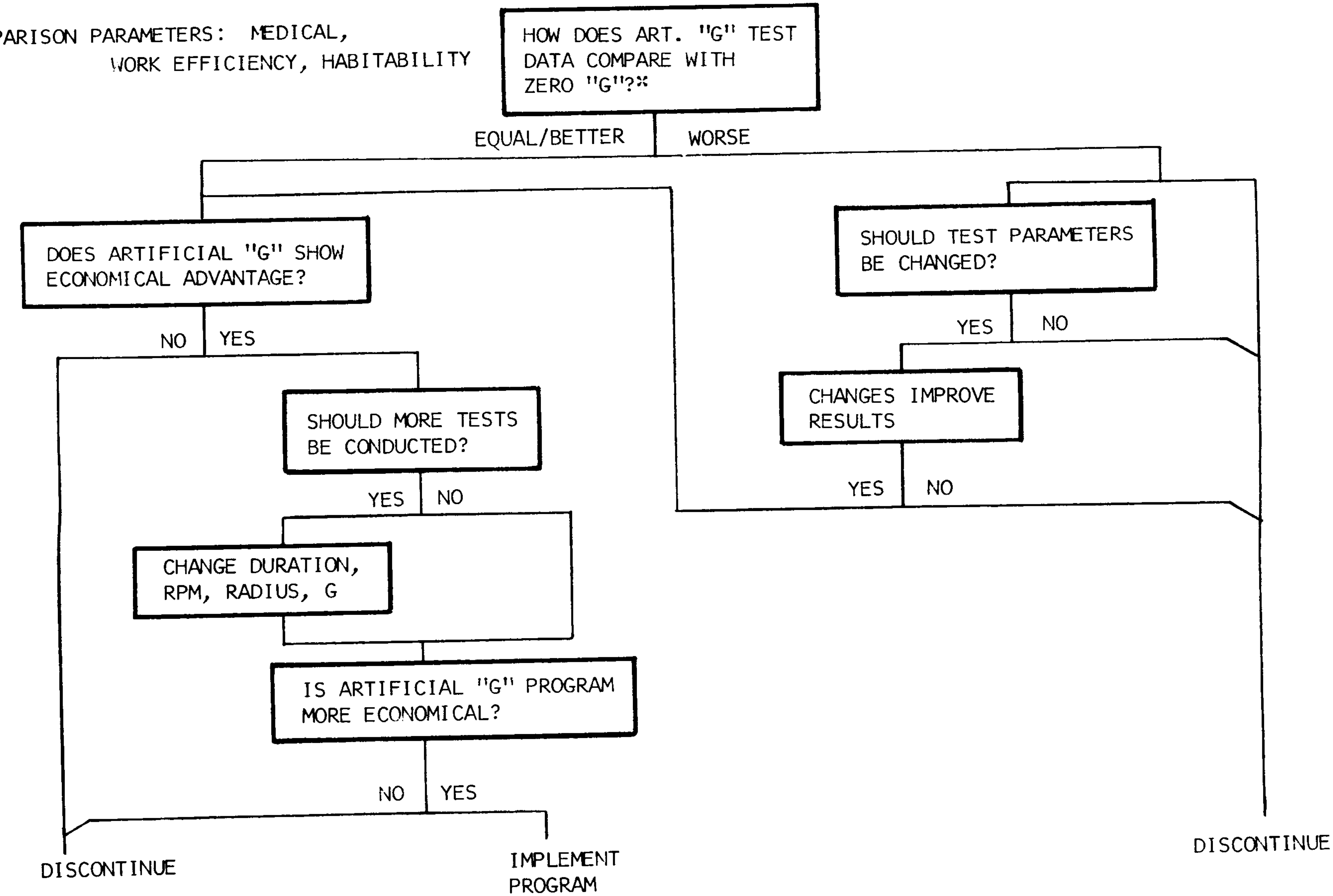
2.3 COMPARISON FACTORS

Three general categories of artificial gravity-zero gravity comparisons are discussed in the following paragraphs.

2.3.1 Medical

Two aspects require investigation. First, the effects of long-term zero gravity on man should be investigated to determine whether or not he can adapt without ill effects. Second, the effects of rotating, partial gravity need to be studied since man may also have difficulty adapting to this type of environment.

The physiological limitations on artificial gravity parameters such as spin radius and rotational rate should be determined. Numerous experiments relating to these parameters have been performed on earth and can be continued less expensively than



⁑ COMPARISON PARAMETERS: MEDICAL, WORK EFFICIENCY, HABITABILITY

ARTIFICIAL "G" - ZERO "G" RATIONALE

FIGURE 2.1

in a space station if some means of correlating this earth data with space data is developed.

2.3.2 Habitability

How significant is crew comfort in space flight? A question of this type is somewhat nebulous because no one really knows the answer. However, industrial studies indicate that man's work efficiency relates directly to his physical comfort. Since long term space flight will present environmental differences and isolation far beyond anything man has yet experienced, it would seem that creature comforts would play a significant role in his ability to efficiently perform his tasks.

2.3.3 Work Efficiency

The previous section on cost effectiveness presented a technique for determining a quantitative comparison for work efficiency. This mission should verify the performance efficiencies derived in Section 1 for a selected gravity level. Thus, a significant factor in comparing artificial to zero gravity will be obtained. It is believed that such a comparison will show that an artificial gravity station cost 20% greater than the cost of a zero gravity station will still be more economical because of manpower output.

3.0 ARTIFICIAL GRAVITY EXPERIMENT - OBJECTIVES AND GUIDELINES

The previous sections have presented various reasons why artificial gravity should be investigated, and how such a program could be developed. The next step is to design a mission to fulfill the implied requirements.

3.1 OBJECTIVES

The objectives of such a mission are categorized similarly to the comparison factors in paragraph 2.3.

3.1.1 Medical

Various experiments - rotating chambers, centrifuge operations and "parabolic flights" - have been conducted on or near Earth and provide a certain amount of data regarding man's capabilities and limitations under these conditions. However, an actual rotating, low-gravity environment can be experienced only in space. Therefore, the artificial gravity mission has three major medical objectives:

A. To determine the effect of a rotational environment on the vestibulo-proprioceptive portion of the human nervous system.

B. To determine these effects on other human organs.

C. To obtain results which may be correlated with ground test procedures.

3.1.2 Work Performance

It should be determined if man's performance in orbital flight can be significantly improved by an artificial gravity environment.

3.1.3 Habitability

It should be determined if crew comfort is significantly improved by an artificial gravity environment.

3.2 GUIDELINES

The guidelines for the study are broken down into the general areas shown in Table 3.1. They were developed from consideration of the various sections of this study.

MISSION GUIDELINES

AREA	GROUNDRULES
MISSION GENERAL OPERATIONAL REQUIREMENTS	1. ORBIT INCLINATION 28.5°. 2. SINGLE UPRATED. 3. BLOCK II COMMAND-SERVICE MODULE. 4. ORBIT ORIENTATION WILL CONSIDER C/SM THERMAL REQUIREMENTS. 5. MISSION DURATION WILL BE UP TO 14 DAYS. 6. TWO MEN IN THE EXPERIMENT MODULE DURING EXPERIMENTATION. 7. ONE MAN IN THE COMMAND MODULE AT ALL TIMES. 8. SPIN RADIUS OF 75 FEET. 9. ROTATION RATE TO BE 3.4 RPM.
SYSTEMS CONDITION FOR SUBSYSTEMS	1. THE HATCH BETWEEN THE COMMAND MODULE AND EXPERIMENT MODULE WILL BE OPEN DURING EXPERIMENTATION. 2. THE EXPERIMENT MODULE WILL BE PRESSURIZED TO ALLOW SHIRT SLEEVE OPERATIONS. 3. INTERFACING WITH THE C/SM SYSTEMS WILL BE CONSIDERED. 4. APOLLO OR GEMINI PROGRAM EQUIPMENT WILL BE USED WHEREVER POSSIBLE. 5. MATERIAL WILL CONFORM TO THE NEW FLAMMABILITY REQUIREMENTS. 6. HAZARD WARNING SYSTEMS, WITH VISUAL AND AUDITORY CAUTION AND WARNING DEVICES, SHALL BE INCORPORATED.
PROGRAMMATIC OVERALL PROGRAM IMPLICATIONS	1. LAUNCH TARGET DATE WILL BE THE FIRST AAP FLIGHT SUBSEQUENT TO THE CLUSTER FLIGHT. 2. THE FLIGHT SHALL NOT INTERFERE WITH MAINSTREAM APOLLO.

TABLE 3.1

4.0 THE MAN

A thorough investigation was made of man's habitability requirements, because the objectives of the artificial gravity study were directed toward determining man's role in space flight. In order to provide a basis for determining the design criteria, an operational definition of habitability was required.

Operational Definition of Habitability

> Habitability includes those characteristics which determine the overall environment of the individual for the space station. These characteristics include equipment orientation in the compartment, food and water, gravitation, personal hygiene, control of noise, vibration, visual stimulus, etc.

In establishing the habitability criteria for the experiment module design, all identifiable potential problem areas associated with human engineering aspects were considered. These potential problems have been identified by:

1. Similarity with those encountered in numerous research designs.
2. Literature survey.
3. Discussions with knowledgeable people associated with space station designs.

Providing personal care and comfort for the crew members is a vital requirement for successful completion of the mission. However, "ideals" and "optimums" used as a basis for current habitability design standards for earth systems must be compromised in order to satisfy space systems constraints. Tradeoffs must be made among the various subsystems and the total system with man as one of the subsystems.

4.1 STUDY GOALS

The major goals of this study were:

1. Establish the human engineering design requirements for the habitability area of the experiment module.
2. Develop a human engineering rationale for the layout of the habitability area.
3. Lay out the habitability area in accordance with the principals determined in 1 and 2.

The approach used to accomplish the above goals was basically one of a mission functional analysis. The major mission phase served as a focal point for that analysis.

SPIN UP AND EXPERIMENTATION TASK DESCRIPTION

FUNCTION	DEFINITION
SYSTEM OPERATION FUNCTIONS	1. MONITOR SPACE STATION SYSTEM STATUS.
	2. CHECK SUBSYSTEM WARNING LIGHTS.
	3. CHECK ELECTRICAL POWER SUPPLY STATUS.
	4. CHECK ENVIRONMENTAL CONTROL SYSTEM STATUS.
	5. PERFORM PERIODIC STABILIZATION CHECK.
	6. PERFORM RECORDING AND LOG WORK.
	7. CHECKOUT COMMUNICATION EQUIPMENT.
	8. PERFORM PERIODIC EQUIPMENT CHECK AND RESUPPLY.
	9. PERFORM CONTINUITY CHECK WITH THE CSM AND/OR RECEIVE CSM STATUS REPORT.
MISSION EXPERIMENTS	1. PERFORM PHYSIOLOGICAL EXPERIMENTS.
	2. PERFORM PSYCHOLOGICAL EXPERIMENTS.
	3. PERFORM DATA GATHERING, CODING, AND STORAGE.
	4. PERFORM DATA PROCESSING AND INTERPRETATION.
	5. PERFORM DATA TRANSMITTAL.
OFF-DUTY FUNCTIONS	1. SLEEP.
	2. RECREATION.
	3. EXERCISE.
	4. FOOD PREPARATION.
	5. FOOD CONSUMPTION.
	6. PERSONAL HYGIENE.
	7. HOUSEKEEPING DUTIES.

TABLE 4.1

4.2 MISSION ANALYSIS

In order to effectively establish the basic requirements for the experiment module, it was necessary to define the functional requirements of the crew members for the various phases of the mission profile. All crew activities and related times are necessarily gross because of the present stage of planning.

Basically, the mission phases are: Boost, Orbit Injection, Station Deployment, Spin-up and Experimentation, Spin-down, Deorbit, Entry, and Landing. The analysis of the Spin-up Experimentation phase (since the major portion of the mission will be spent in this phase) investigated the station functions, the crew activities required to accomplish those functions, the habitability areas in which those functions are performed, and the crew time required for those functions. The other mission phases were not analyzed since they have little impact on the habitability area from a human engineering viewpoint.

4.2.1 Spin-up and Experimentation Phase

The Spin-up and Experimentation phase was analyzed to determine the functions necessary to successfully complete it.

After the experiment module is extended and checked out, the experiment module crew is ready for transfer. One member of the crew will remain in the CSM with the primary function of monitoring the station operations. The functions of the two crew members in the habitability area are defined in Table 4.1.

Although the exact duties of the crew in monitoring and control are unresolved at this stage in planning, it is certainly inefficient to require 24-hour monitoring by the crew when an auditory warning device can provide the reliability required. In keeping with this concept, a crewman may leave his station at certain intervals to go to the hygiene area, crew quarters area, or to pursue recreational activities or rest.

The distribution of crew hours for the various functions is shown in Table 4.2. The hours breakdown is based on a one man-day or 24 hours total.

TABLE 4.2 DISTRIBUTION OF CREW HOURS FOR ONE MAN

FUNCTION	HOURS
System Operation (Monitoring, Control and Maintenance)	2
Mission Experiments	9.5
Personal Activities:	
Hygiene	1.5
Food	1
Recreation and Exercise	2
Sleep	8
TOTAL MAN HOURS PER DAY	24

HABITABILITY AREAS AND RELATED FUNCTIONS

FUNCTIONS	EXPERIMENTAL/ WORK	CREW QUARTERS	HYGIENE AREA
MONITOR SPACE STATION SYSTEM STATUS	X		
CHECK SUBSYSTEM WARNING LIGHTS	X		
CHECK ELECTRICAL POWER SUPPLY STATUS	X		
CHECK ENVIRONMENTAL CONTROL SYSTEM	X		
PERFORM PERIODIC STABILIZATION CHECKS	X		
PERFORM RECORDING AND LOG WORK	X		
CHECKOUT COMMUNICATION EQUIPMENT	X		
EQUIPMENT CHECKS AND RESUPPLY	X	X	X
PERFORM PHYSIOLOGICAL EXPERIMENTS	X		
PERFORM DATA GATHERING, CODING AND STORAGE	X		
PERFORM DATA PROCESSING	X		
SLEEP		X	
RECREATION		X	
EXERCISE		X	
FOOD PREPARATION	X		
FOOD CONSUMPTION	X		
PERSONAL HYGIENE			X
HOUSEKEEPING	X	X	X

TABLE 4.3

4.2.2 Functional Allocation

The approach used in this study was to list the functions required to accomplish the major mission phase (Spin-up and Experimental Phase) and to establish areas suitable to accomplish those functions. Table 4.3 presents a listing of the functions and the areas in which they will be performed.

4.3 GROUND RULES AND RATIONALE

This portion of the study covers ground rules and human engineering rationale for the design of the experiment module habitability area. The conclusions are based on a functional analysis of the Spin-up and Experimentation mission phase requirements, existing literature, and present program requirements.

4.3.1 Ground Rules

Establishing basic habitability requirements for an experiment module required a number of basic ground rules. For this study the following ground rules were developed.

1. Crew Size: 3 astronauts
2. Mission:
   Launch and Setup: 1 day
   Spin-up: 1 day
   Experiment: 7 days
   Spin down: 1 - 4 hours
   Return: 1 day
   Total Mission Time: 10 days
3. Spin Radius: 75 feet (nominal)
4. G Load to be Maintained During Mission Spin: .3g $\pm$ .01 g
5. Habitable Quarters:
   a. Provide shirt sleeve environment quarters for two crewmen to live and work for a maximum of 10 days.
   b. One man will remain in the CSM at all times and two men will remain in the experiment module.
   c. After spin-up, the only reason for the crewmen to leave their respective areas will be because of an emergency.
   d. Radial traffic should be kept to a minimum.
   e. Transport across the spin axis, and human activity at the spin axis should be prohibited unless the hub is non-rotating.
   f. The living-working compartment should be located as far as possible from the axis of rotation.
   g. The compartment should be oriented so that the direction of traffic--i.e., the major dimension of the compartment--is parallel to the vehicle spin axis.
   h. Crew duty-station positions should be oriented so that, during normal activity, the lateral axis through

the crew member's ears is parallel to the spin axis. In conjunction with this requirement, the work console instruments and controls should be designed so that left-right head rotations and up-down arm motions are minimized.

i. Sleeping bunks should be oriented with their long axes parallel to the vehicle spin axis.

4.3.2 Habitability Arrangement Rationale

The experiment module habitability configuration shown in Figure 4.1 was separated into three major areas:

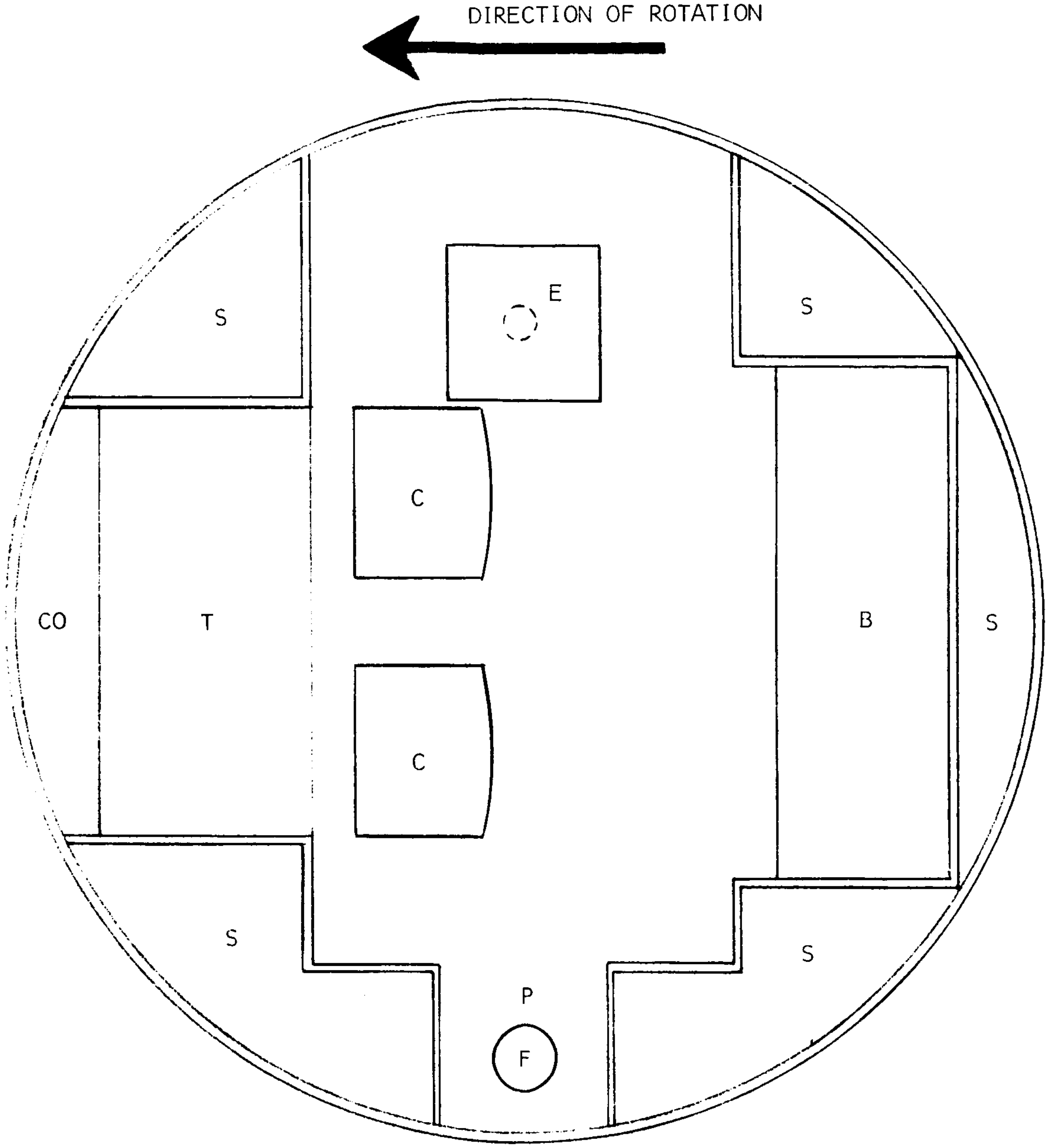
1. Experimental/Work Area: The seating arrangement and location in the experimental/work area allows the crew during normal activity to sit so that the axis through crew member's ears is parallel to the spin axis. Easy access to and from the seats, to the console, and to the other areas is provided by the seat positions.

   The experimental/work console is designed to utilize maximum up/down head movements while limiting other head motions. Figures 4.2 through 4.6 determine the requirement for this arrangement by defining the reactions to various head motions.
2. Crew Quarters Area: The beds are oriented with their long axes parallel to the vehicle spin axis. They are stowed when not in use and the area utilized for exercise or the donning of space suits in an emergency. In the bed, the head will be oriented such that most of the head movement(left and right movement) will be in the rotation plane.
3. Personal Hygiene Area: The personal hygiene area, based on the present Apollo configuration, is located to give maximum space between it and the other areas occupied by the crew to minimize annoyance from odors. Due to the 10-day duration of the mission, the fecal matter can be collected in plastic bags, treated to prevent bacterial activity and suppress odor production, and stored in special isolated compartments.

In summary, the habitability area design should have the following goals:

1. Minimize possibility of the crew making errors of either omission or commission.
2. Minimize psychological and physiological fatigue factors.
3. Increase the effectiveness in both amount and quality of the work experiments to be conducted by the crew.

DIRECTION OF ROTATION



FLOOR PLAN

KEY:

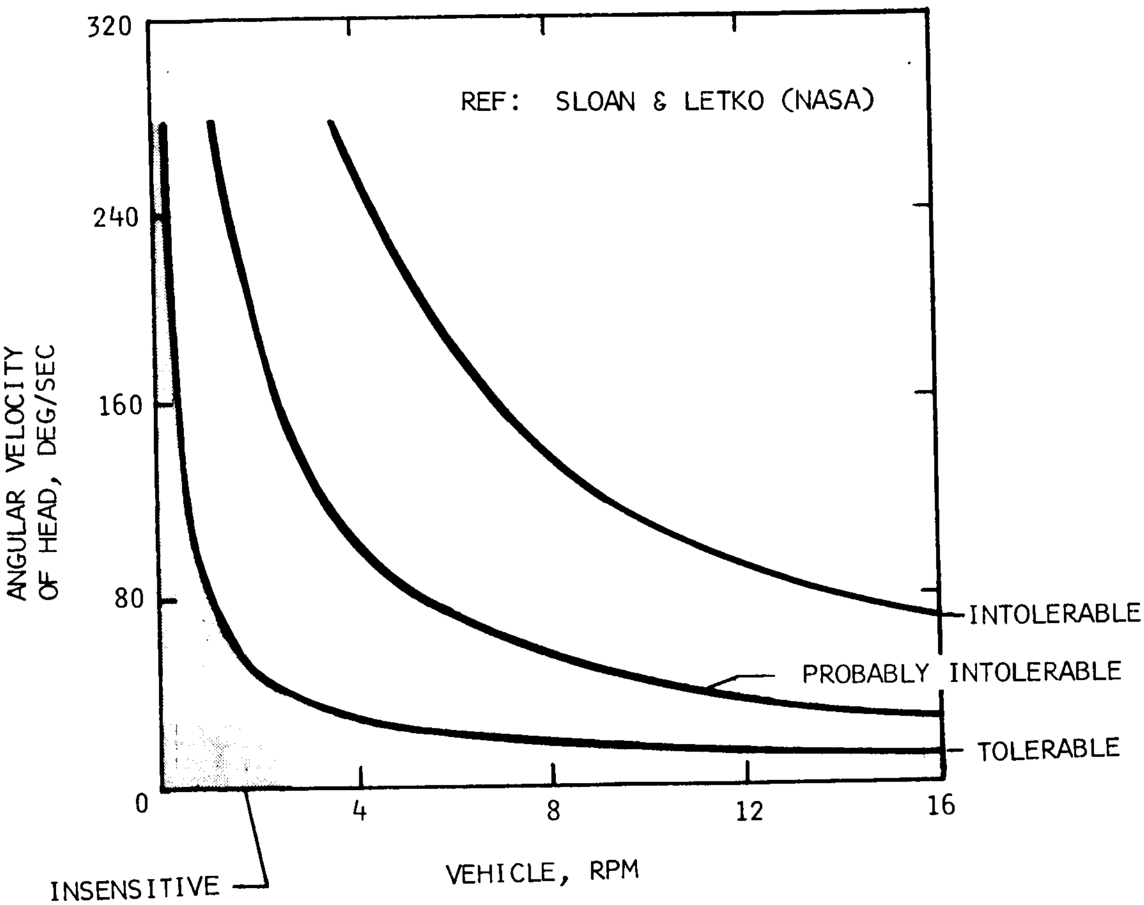
S - STOWAGE COMPARTMENTS
B - BUNK BEDS (ROLL-UP TYPE)
C - CHAIR
T - WORK AND EXPERIMENT TABLE
P - PERSONAL HYGIENE FACILITY
F - FECAL CANISTER
CO - CONSOLE (INFORMATION AND EXPERIMENTS)
E - EXPERIMENTAL CHAIR

NOTES:

1. DESIGN BASED UPON 12' DIAMETER
2. SCALE 1/2" = 1'

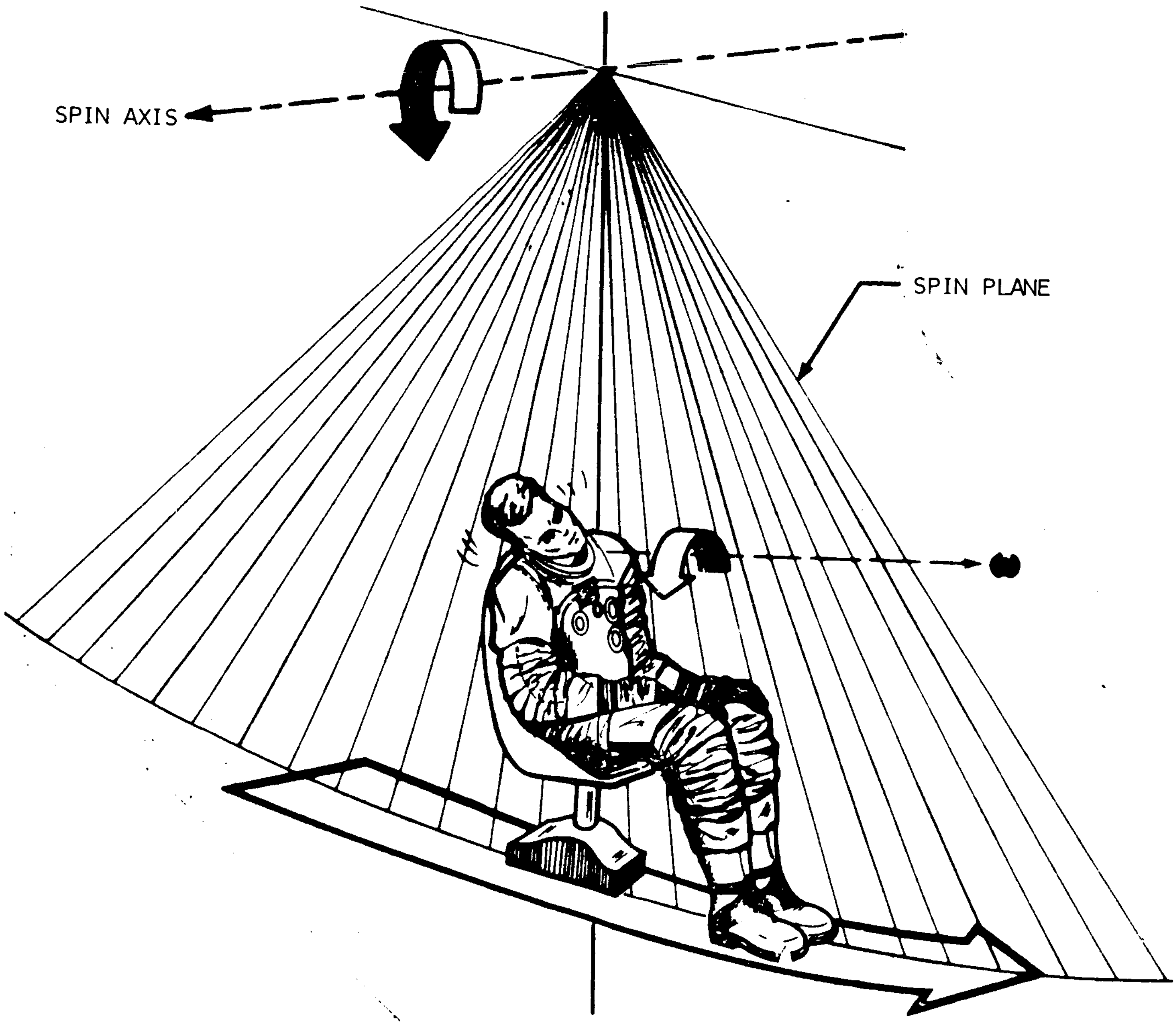
PRELIMINARY DESIGN OF HABITABILITY AREA

FIGURE 4.1



HEAD MOTION TOLERANCE BOUNDARIES

FIGURE 4.2

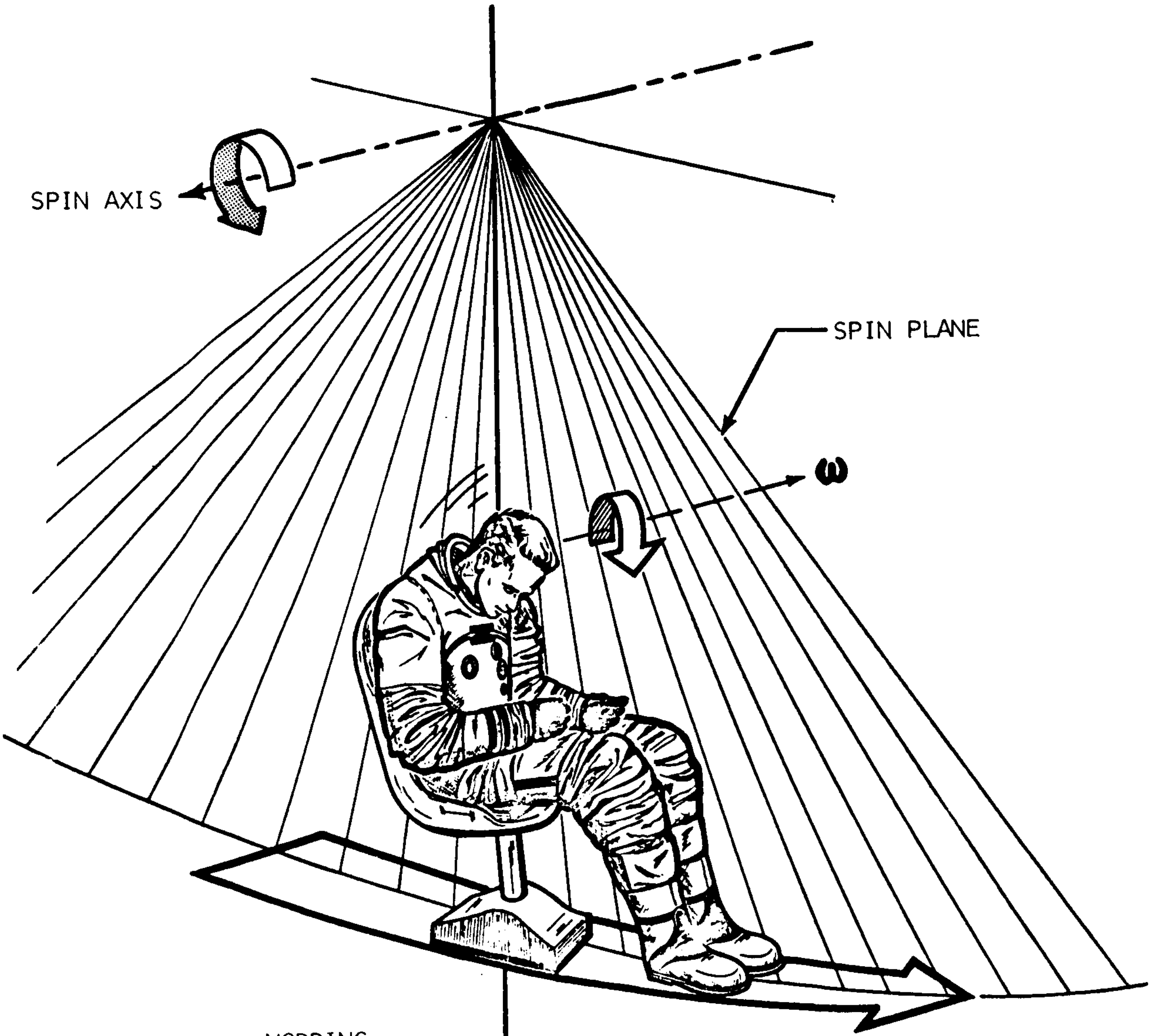


HEAD MOVEMENT — TILTING

VESTIBULAR EFFECT — ILLUSION OF PITCHING UP

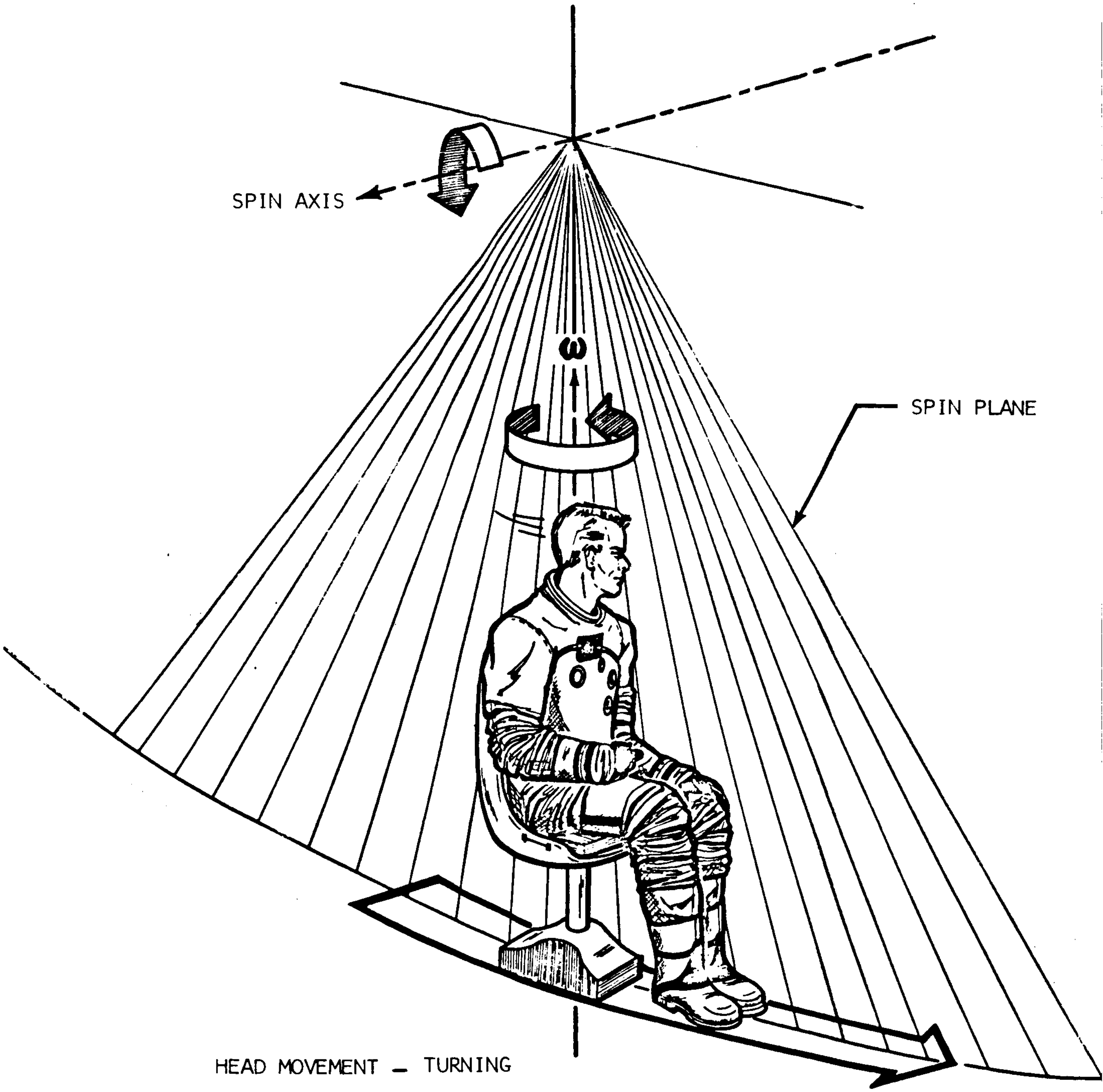
VESTIBULAR REACTIONS

FIGURE 4.3



VESTIBULAR REACTIONS

FIGURE 4.4

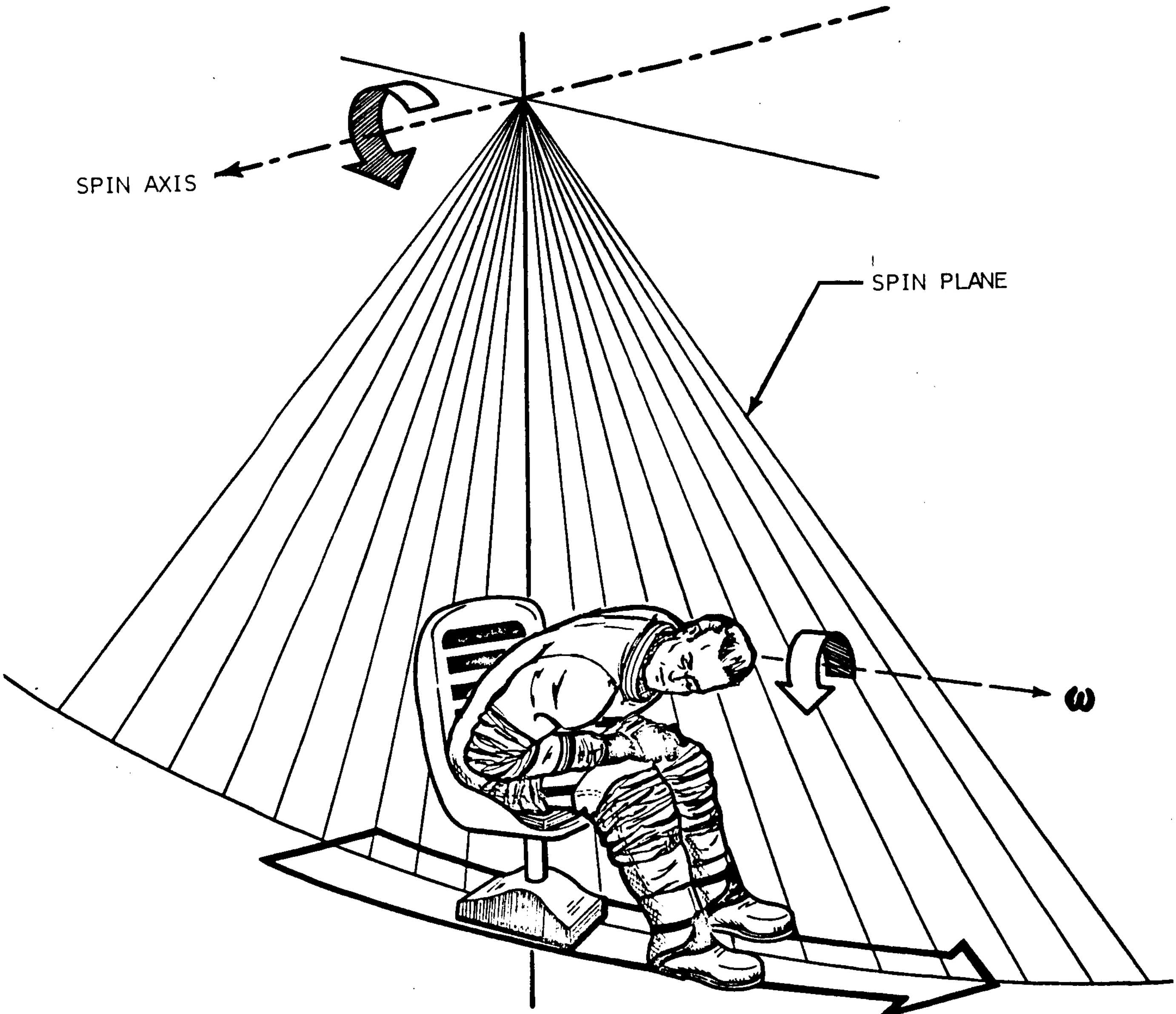


HEAD MOVEMENT — TURNING

VESTIBULAR EFFECT — ILLUSION OF ROLLING OF ROOM
COUNTER-CLOCKWISE IN SPIN PLANE

VESTIBULAR REACTIONS

FIGURE 4.5

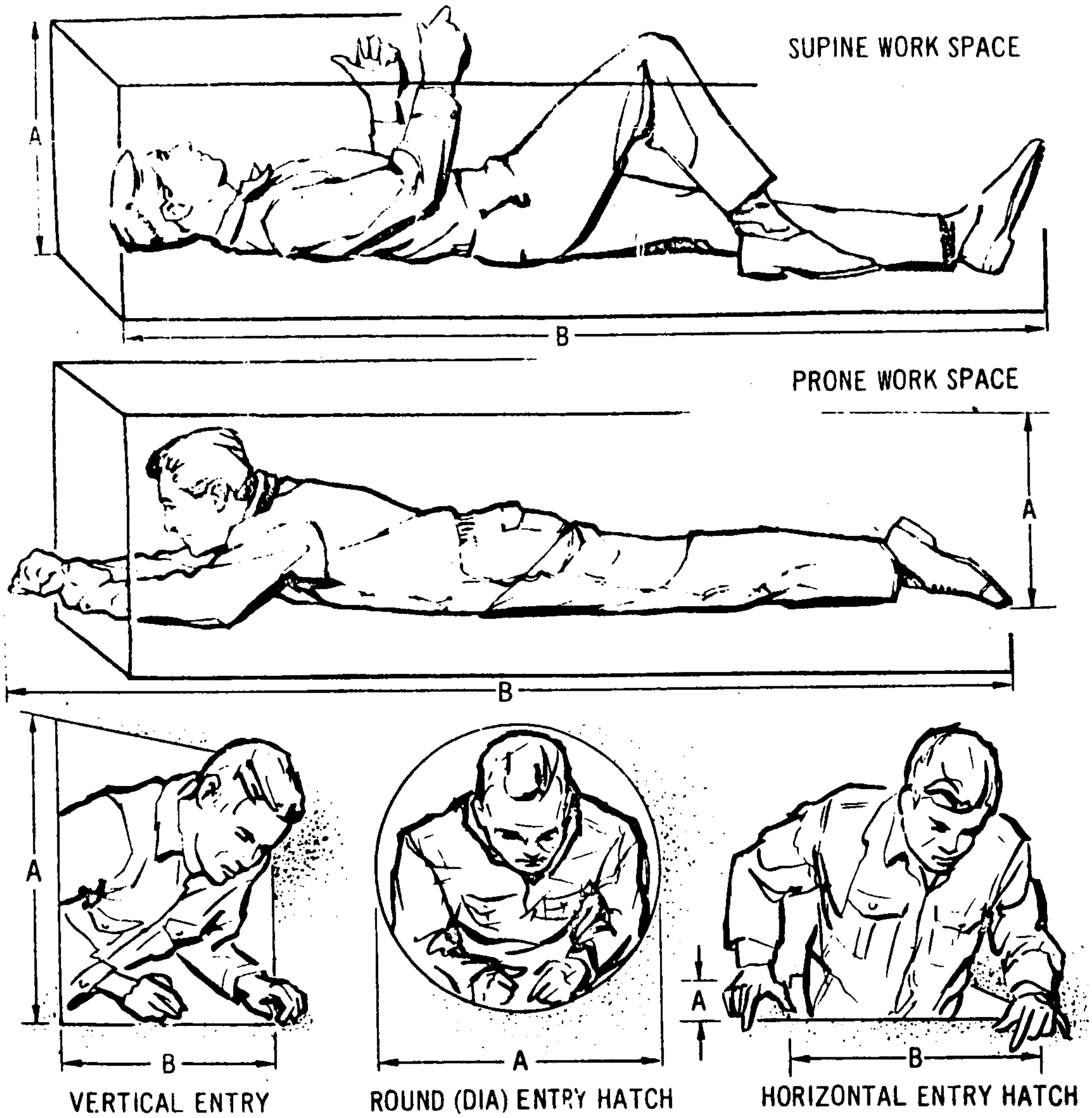


HEAD MOVEMENT – BENT FORWARD AND TURNING

VESTIBULAR EFFECT – ILLUSION OF PITCHING UP

VESTIBULAR REACTIONS

FIGURE 4.6



		BULKY PROTECTIVE CLOTHING	LIGHT CLOTHING
SUPINE WORK SPACE	"A"	26" MIN	20" MIN
	"B"	78" MIN	78" MIN
PRONE WORK SPACE	"A"	24" MIN	17" MIN
	"B"	96" MIN	96" MIN
VERTICAL ENTRY HATCH	"A"	20" MIN	12" MIN
	"B"	32" MIN	24" MIN
ROUND (DIA) ENTRY HATCH	"A"	32" MIN	24" MIN
HORIZONTAL ENTRY HATCH	"A"	24" MIN	
	"B"	32" MIN	22" MIN

MINIMUM ACCESS REQUIREMENTS
(SHIRT SLEEVE CREWMAN)

FIGURE 4.7

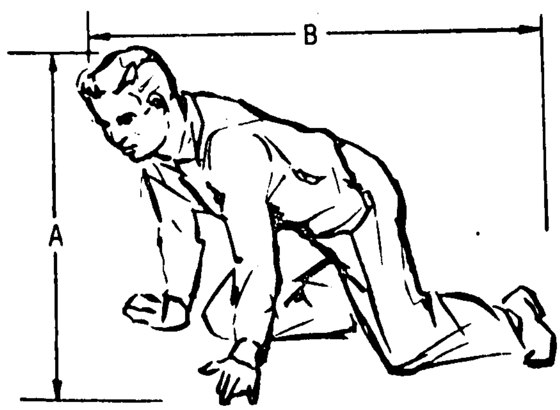
SQUATTING WORK SPACE

KNEELING WORK SPACE

		BULKY PROTECTIVE CLOTHING	LIGHT CLOTHING
SQUATTING WORK SPACE	"A" "B"	51 MIN 40 MAX	48 MIN 36 MIN
KNEELING WORK SPACE	"A" "B"	59 MIN 50 MIN	56 MIN 42 MIN
STOOPING WORK SPACE	"A"	44 MIN	36 MIN
KNEELING CRAWL SPACE	"A" "B"	38 MIN 62 MIN	31 MIN 59 MIN

NOTE: ALL DIMENSIONS IN INCHES.

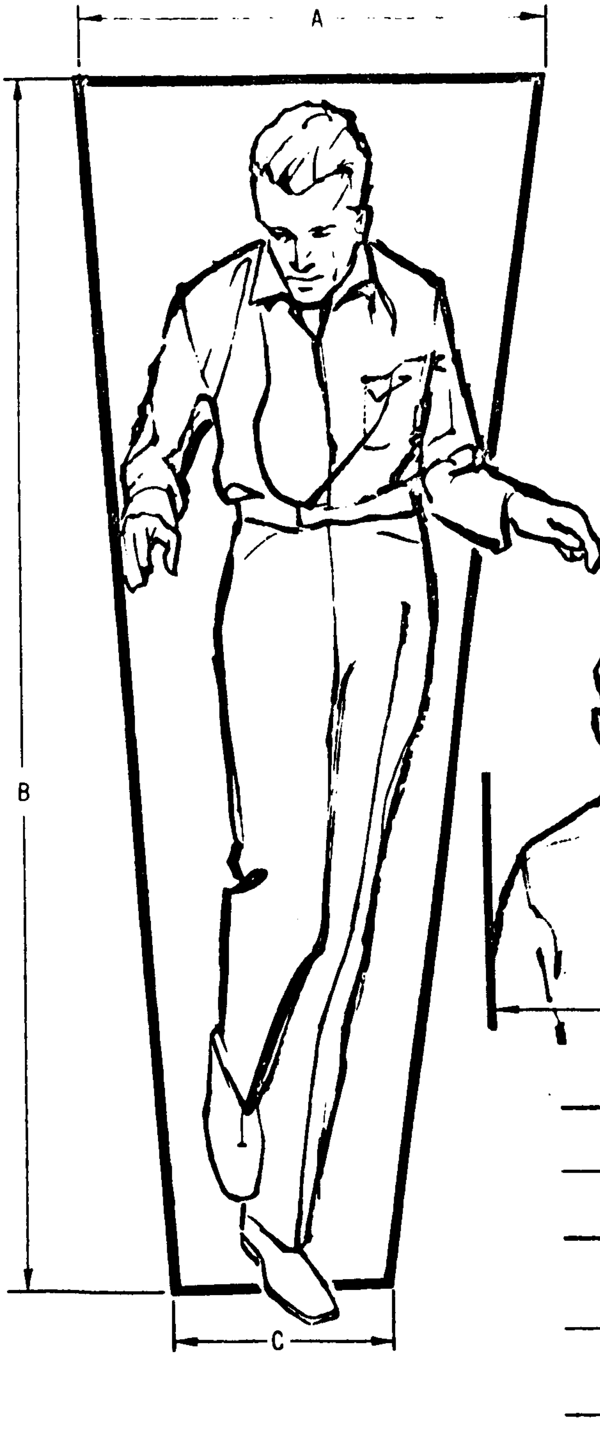
STOOPING WORK SPACE

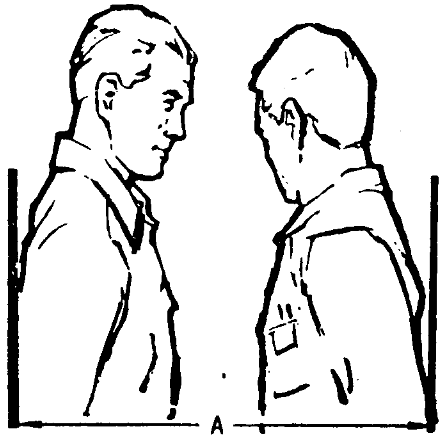


KNEELING CRAWL SPACE

MINIMUM WORK SPACE REQUIREMENTS
(SHIRT SLEEVE CREWMEN)

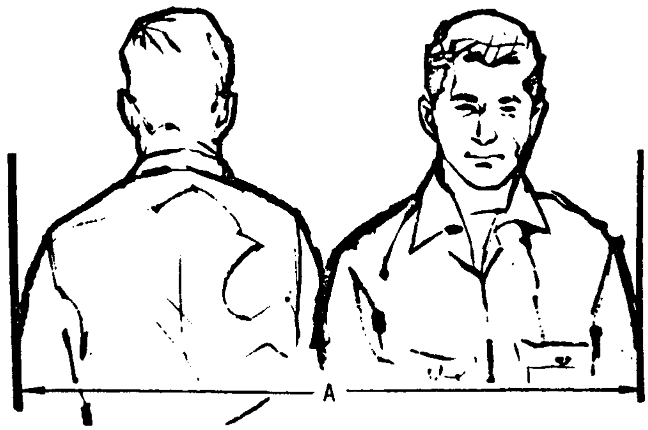
FIGURE 4.8





2 MEN PASSING FACING

A	36" ADEQUATE. 30" MIN.



2 MEN PASSING ABREAST

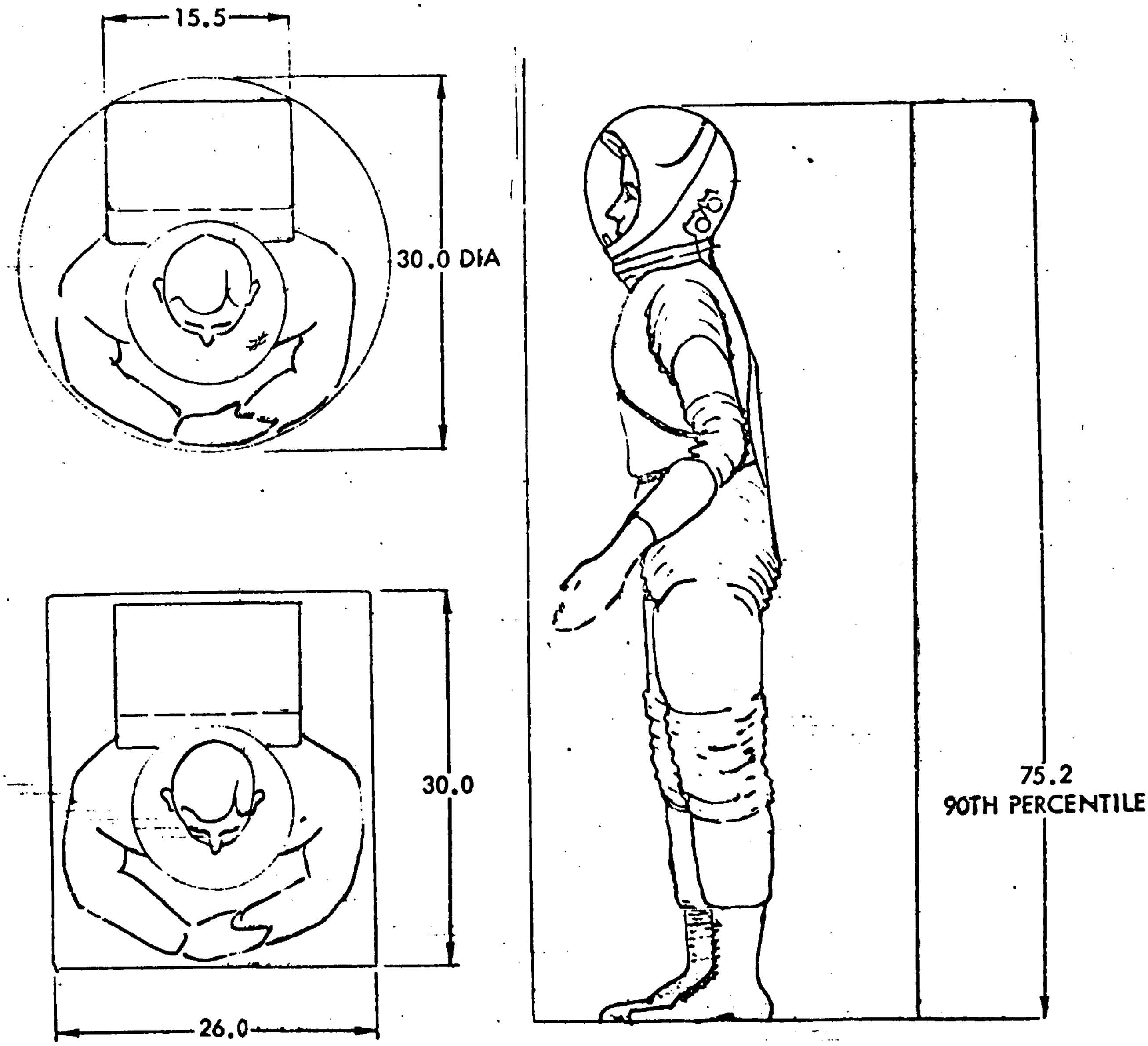
A	54" ADEQUATE. 42" MIN.

CATWALK

A	32" MIN BULKY PROTECTIVE CLOTHING. 24" MIN LIGHT CLOTHING.
B	80" MIN UPRIGHT. 63" MIN CROUCHING.
C	15" MIN BULKY PROTECTIVE CLOTHING. 12" MIN LIGHT CLOTHING.

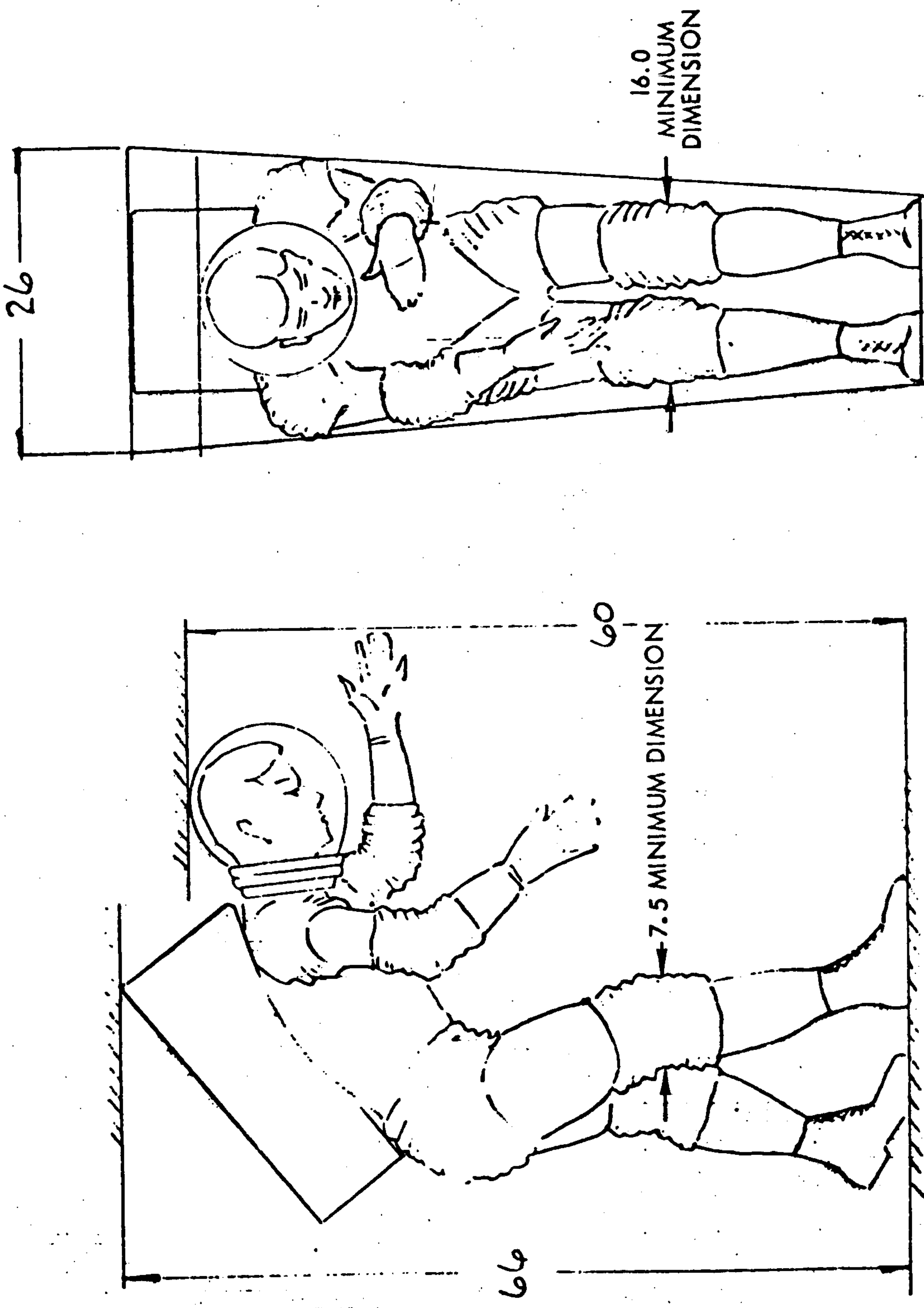
PASSAGEWAY REQUIREMENTS (SHIRT SLEEVE CREWMAN)

FIGURE 4.9



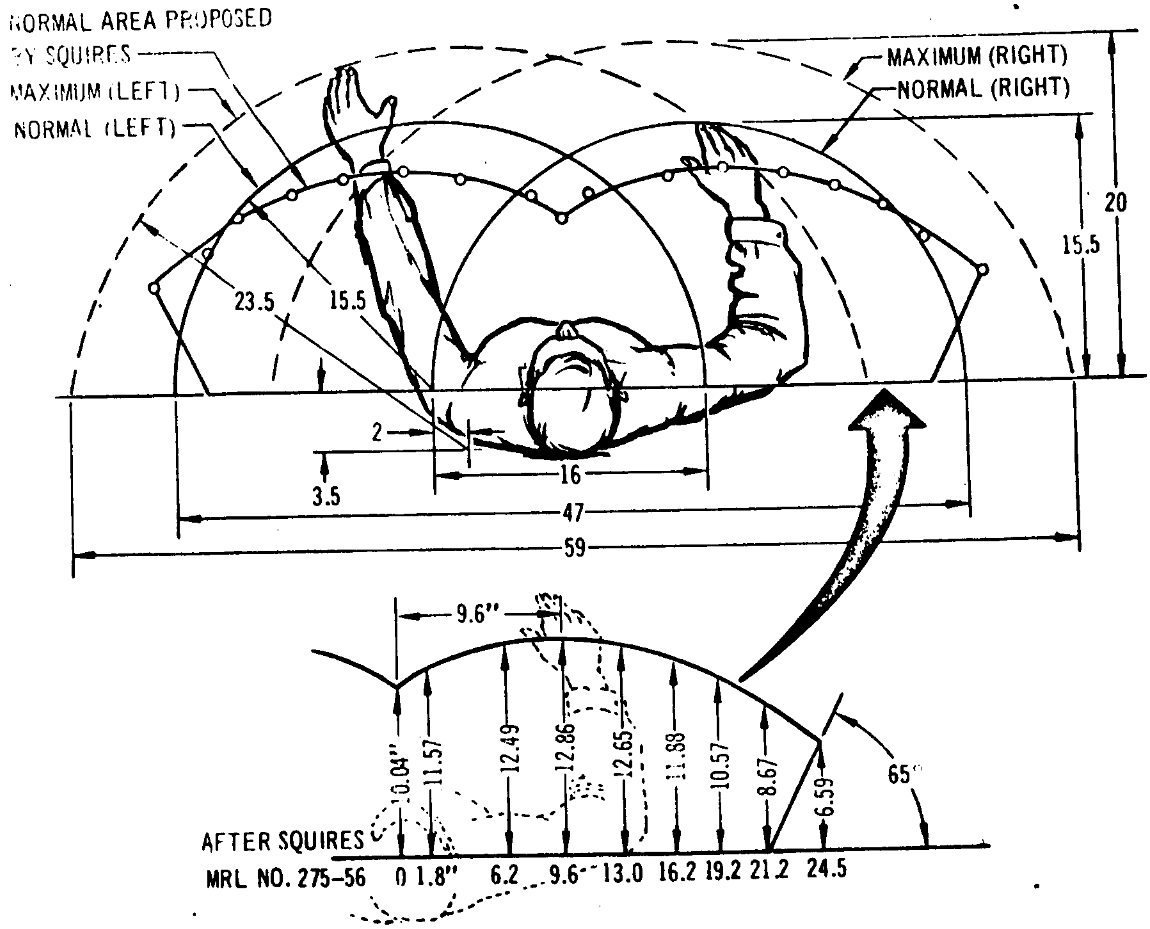
HATCH REQUIREMENTS (PRESSURE SUITED CREWMEN)

FIGURE 4.10



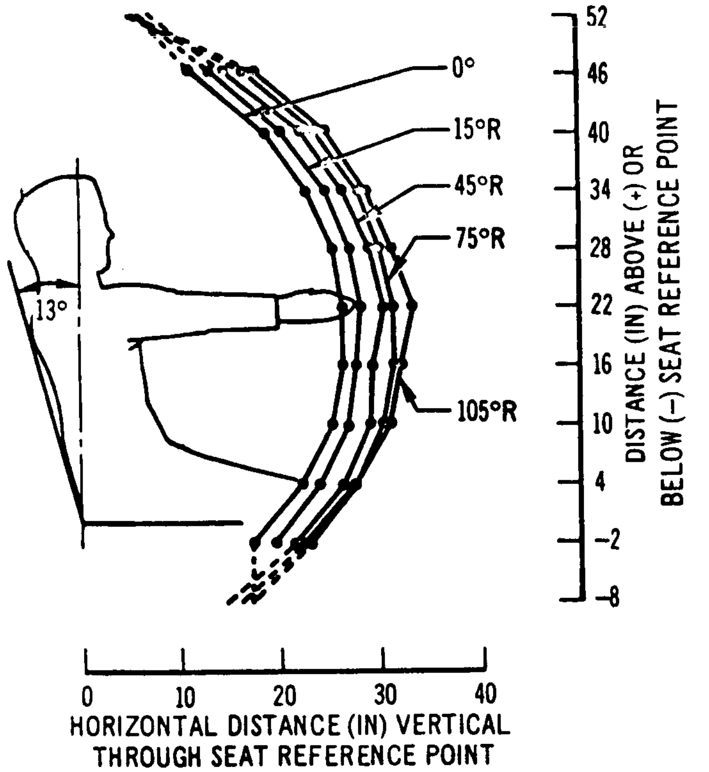
PASSAGEWAY REQUIREMENTS
(PRESSURE SUITED CREWMEN)

FIGURE 4.11



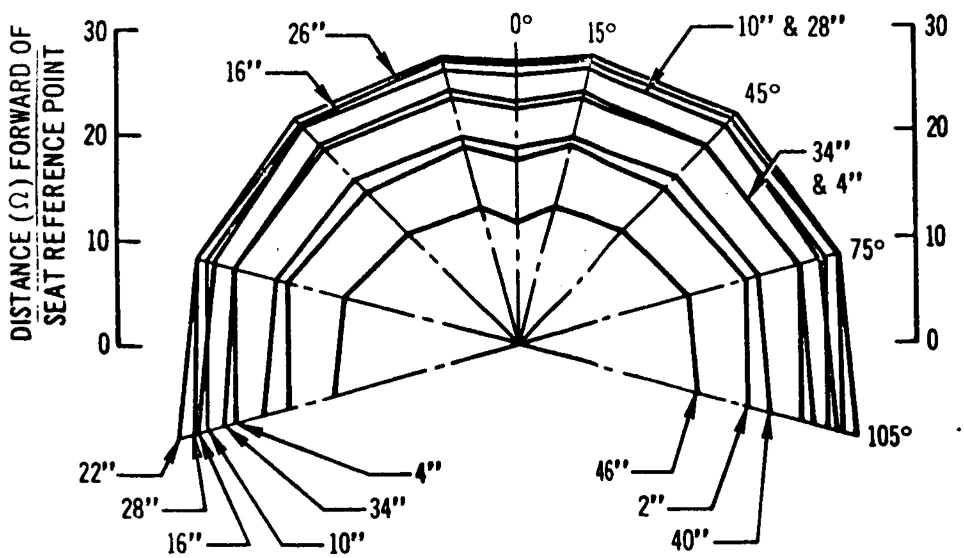
HORIZONTAL WORK AREAS

FIGURE 4.12



MAXIMUM DISTANCES WHICH CAN BE REACHED BY 97% OF THE POPULATION* AT EACH POSITION. THE ELLIPTICAL ARCS INDICATE THE MAXIMUM BOUNDARIES OF THE WORKING AREA FOR OPERATION OF MANUAL CONTROLS (AT RIGHT ANGLES FROM 0° TO 105° TO THE RIGHT) FOR THIS GROUP. SEAT BACK ANGLE 13°.

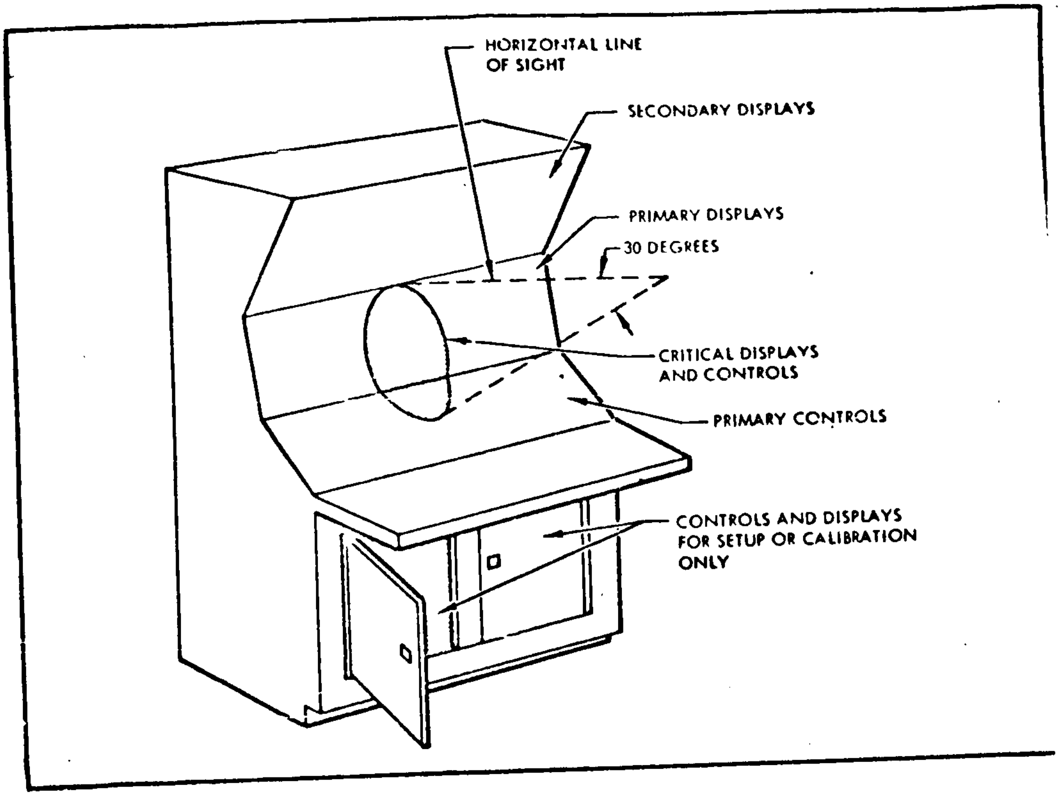
* 139 NAVY PILOTS & NON-PILOTS

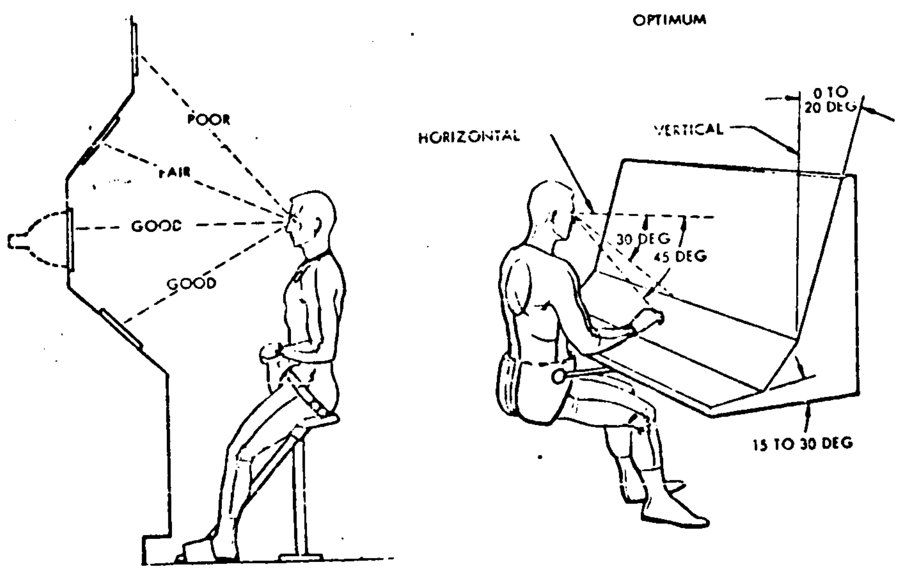


MAXIMUM DISTANCES WHICH CAN BE REACHED BY 97 PER CENT OF THE POPULATION AT EACH POSITION. THE ELLIPTICAL ARCS INDICATE MAXIMUM BOUNDARIES FOR THIS GROUP FOR OPERATION OF MANUAL CONTROLS AT VARIOUS HORIZONTAL LEVELS. SEAT BACK 13° FROM VERTICAL.

VERTICAL AND HORIZONTAL REACH DISTANCES

FIGURE 4.13





DISPLAY CONSOLE REQUIREMENTS

FIGURE 4.14

4.4 MISSION EXPERIMENTS

The principal objective of the artificial gravity experiment is to determine whether man can function more proficiently in artificial gravity than in zero gravity without detrimental performance effects. Thus, psychological, physiological, and medical experiments are of the utmost importance. A list of the general experiments is presented here, and discussed in detail in Section 5.

a. Metabolic cost	d. Vestibular
b. Cardiovascular series	e. Time and motion
c. Bone and muscle	f. Sensory motor

4.5 DESIGN DIMENSIONS

The experiment module design dimensionally reflects the shirt-sleeve environment ground rule previously mentioned. However since space-suited movements may be necessary (in initial occupation of the module and in emergency operations), the areas used for those functions must be dimensioned accordingly.

WADC Technical Report 52-321 "Anthropometry of Flying Personnel", September, 1954, was consulted to provide minimum dimensions for both the shirt-sleeve and the space suited environment. Figures 4.7 through 4.14 present the minimum dimensions for both environmental conditions.

The experiment module will be dimensioned to accommodate the full range of USAF flying personnel. Generally, this is assumed to mean that a man between the 5th and 95th percentiles can use the facilities easily, while the top and bottom 5 percentile may have some difficulty.

4.6 METABOLIC REQUIREMENTS

It was felt that the volume available to the crew would vary their metabolic requirements. It was theorized that a cabin having a large volume available to the crewmen would show few, if any, metabolic differences from the normal life situation of a relatively sedentary office worker. Conversely, life in a very small volume should reflect drastically reduced metabolic levels which are almost commensurate with bedrest situations.

To test these theories, three confinement studies were conducted. In all three studies, the subjects were confined continuously, without outside contact except by intercom at programmed intervals. All requirements for eating, sleeping, personal hygiene, and investigative procedures were provided on board. The volume and duration are presented in Table 4.4.

TABLE 4.4 METABOLISM STUDIES

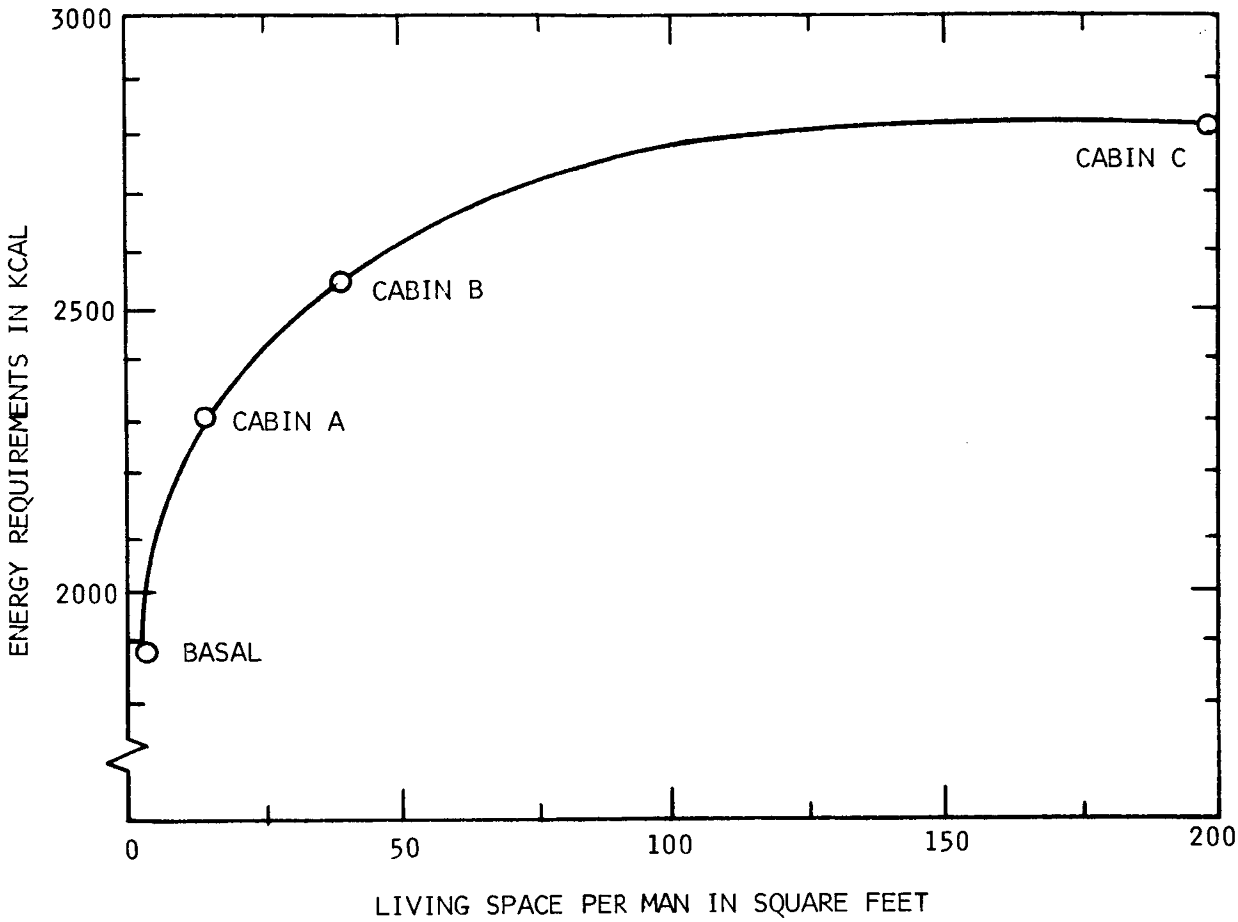
CABIN	EXTERNAL VOLUME CU. FEET	INTERNAL SIZE VOLUME/ MAN FT^3	FLOOR AREA/ MAN FT^2	NUMBER OF MEN	LENGTH OF STAY-DAYS
A	450	70	39	3	7
B	3500	375	37	4	7
C	3200	800	200	2	4

When the metabolic requirements of the subjects were evaluated, it was found that they varied as expected. In Cabin A where movement, and consequently, activity were reduced to a minimum, the energy needs were almost those of the bedrest state (2300 Kcal per man-day). In Cabin B, because space was available for movement, activity increased accordingly but was still on the lower limits characteristic of a sedentary occupation (2550 Kcal per man-day). Cabin C, on the other hand, with a large amount of free space allowed activity levels well within those of the average office worker (2800 Kcal per man-day). It is apparent that the activity levels within these cabins varied considerably even though the mission tasks were similar. Figure 4.15 relates the energy requirements of man to the amount of living space available.

4.7 HUMAN TOLERANCES

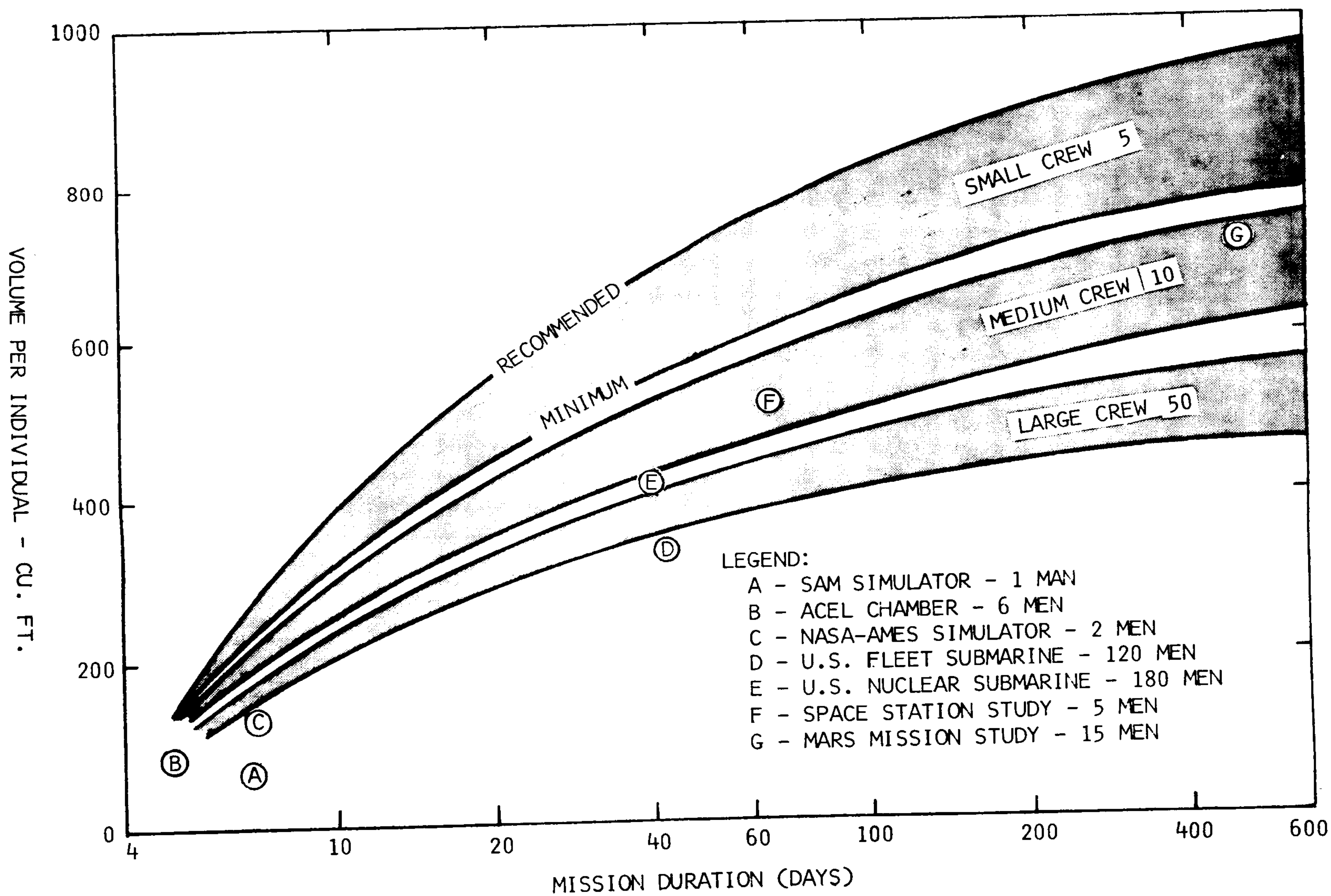
Man has certain physical tolerances within which he must remain if he is to function properly. These tolerances are depicted in chart form as an aid to effective presentation.

Figure 4.16 - Recommended space per man
Figure 4.17 - Wall angle visual tolerances
Figure 4.18 - Acceptable combination of rotation radius
Figure 4.19 - Limiting vibration levels
Figure 4.20 - Atmospheric comfort level
Figure 4.21 - Noise tolerance



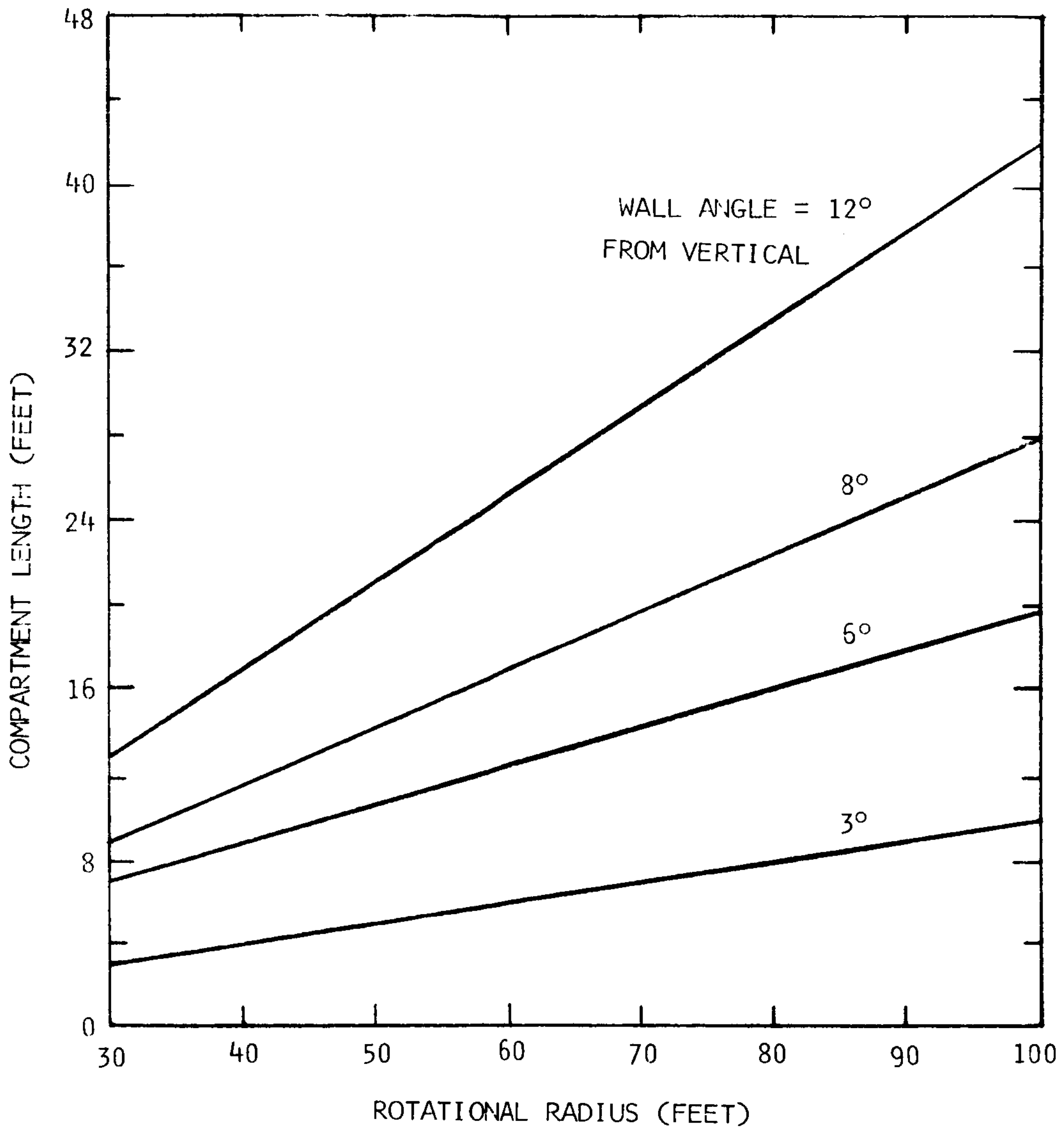
ENERGY REQUIREMENTS PER AVAILABLE VOLUME

FIGURE 4.15



HUMAN SUPPORT VOLUMETRIC REQUIREMENTS

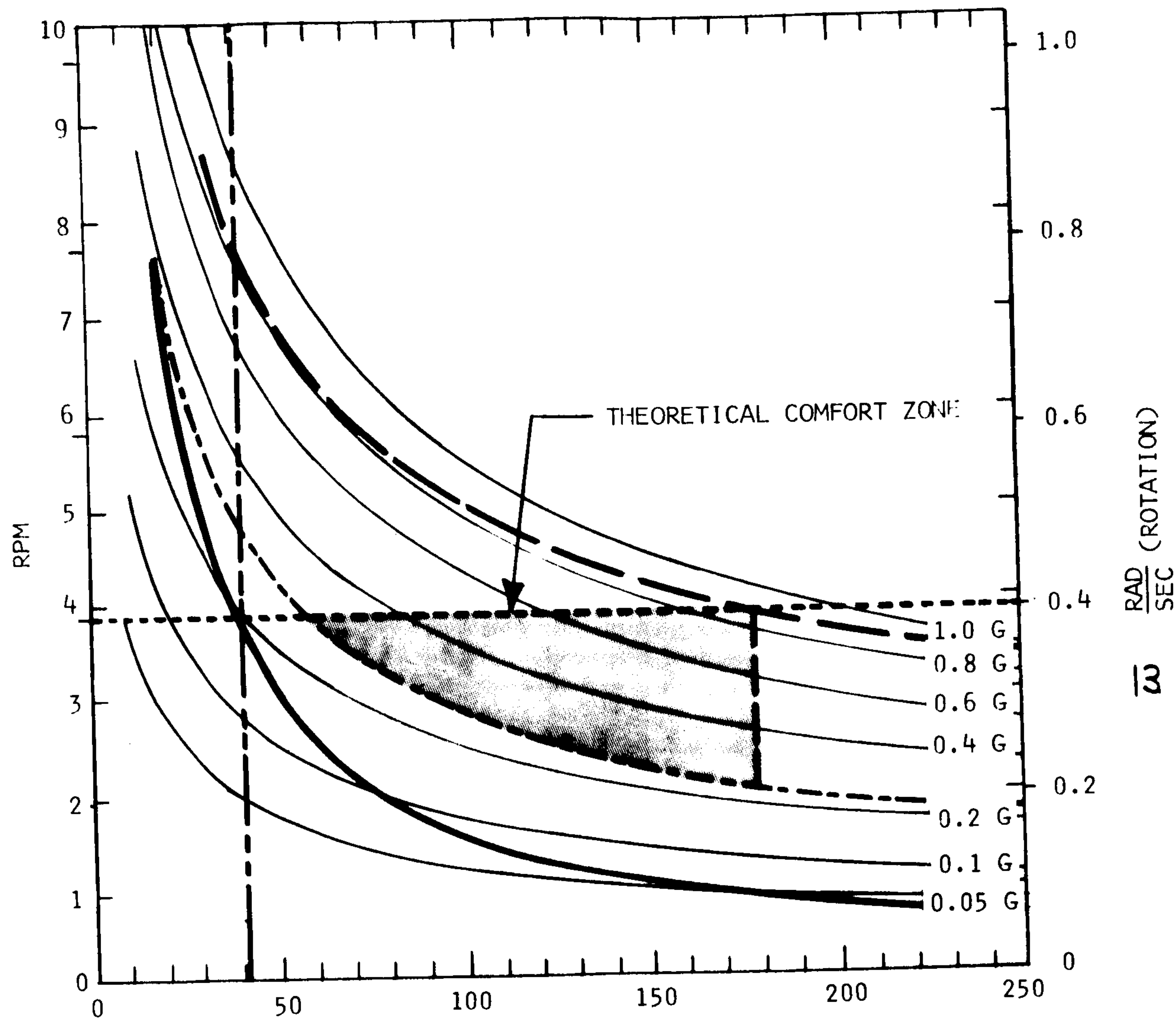
FIGURE 4.16



THE WALL ANGLES ARE THOSE WITH RESPECT TO THE MAN'S VERTICAL AS HE STANDS IN A SPACE STATION. IF CORNERS ARE BROKEN UP AND CURVED SURFACES ARE USED, THE 12-DEGREE ANGLE MIGHT BE ACCEPTABLE. THE 3-DEGREE VALUE IS NEAR THRESHOLD OF DISTORTION FOR TILTED ROOMS WHEN JUDGMENTS ARE NOT AIDED BY CLUES DUE TO OBJECTS PLACED NEAR THE CORNERS.

COMPARTMENT LENGTH CONSIDERATIONS

FIGURE 4.17

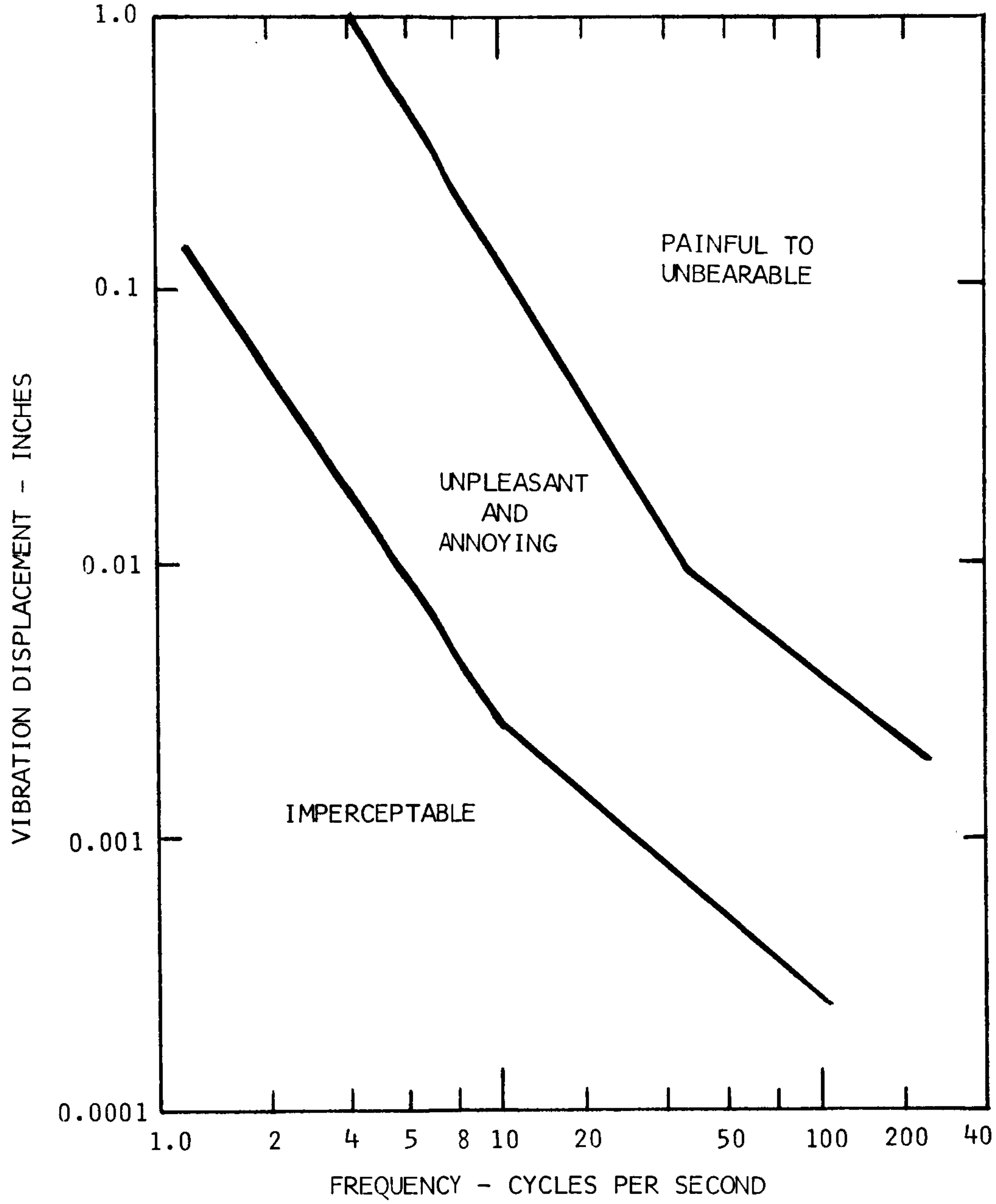


HUMAN FACTORS DESIGN LIMITS

- UPPER LIMIT ON $\overline{\omega}$ -(CANAL SICKNESS)
- UPPER LIMIT ON "G" -(LOCOMOTIVE EFFECTS)
- LOWER LIMIT ON "G" -(LOCOMOTIVE EFFECTS)
- LOWER LIMIT ON $\overline{r}$ -(GRAVITY GRADIENT)
- LOWER LIMIT ON $\overline{r}$, $\overline{\omega}$ -(DOLE, 50% Δ "G")

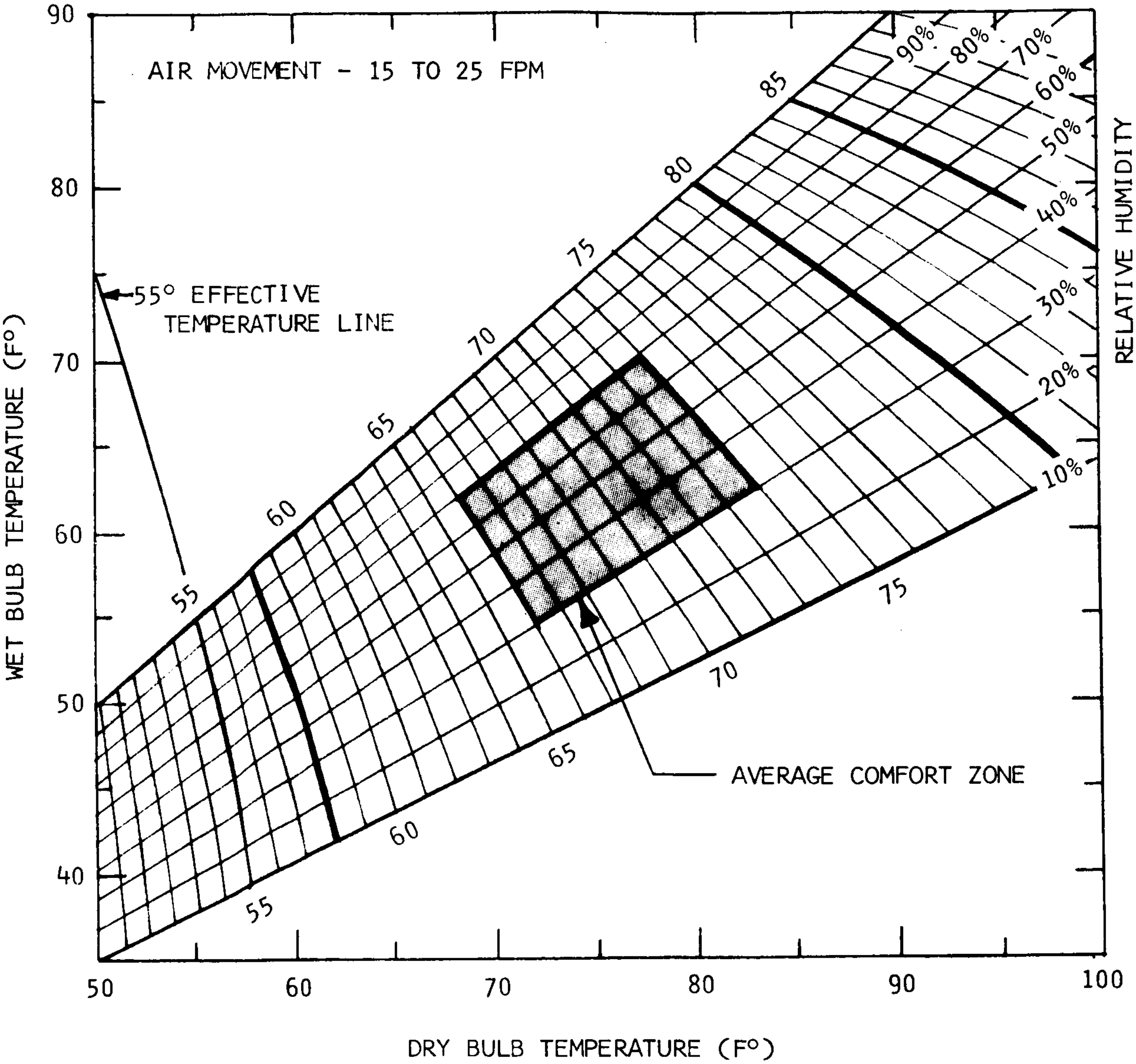
ACCEPTABLE COMBINATION OF ROTATION RADIUS

FIGURE 4.18



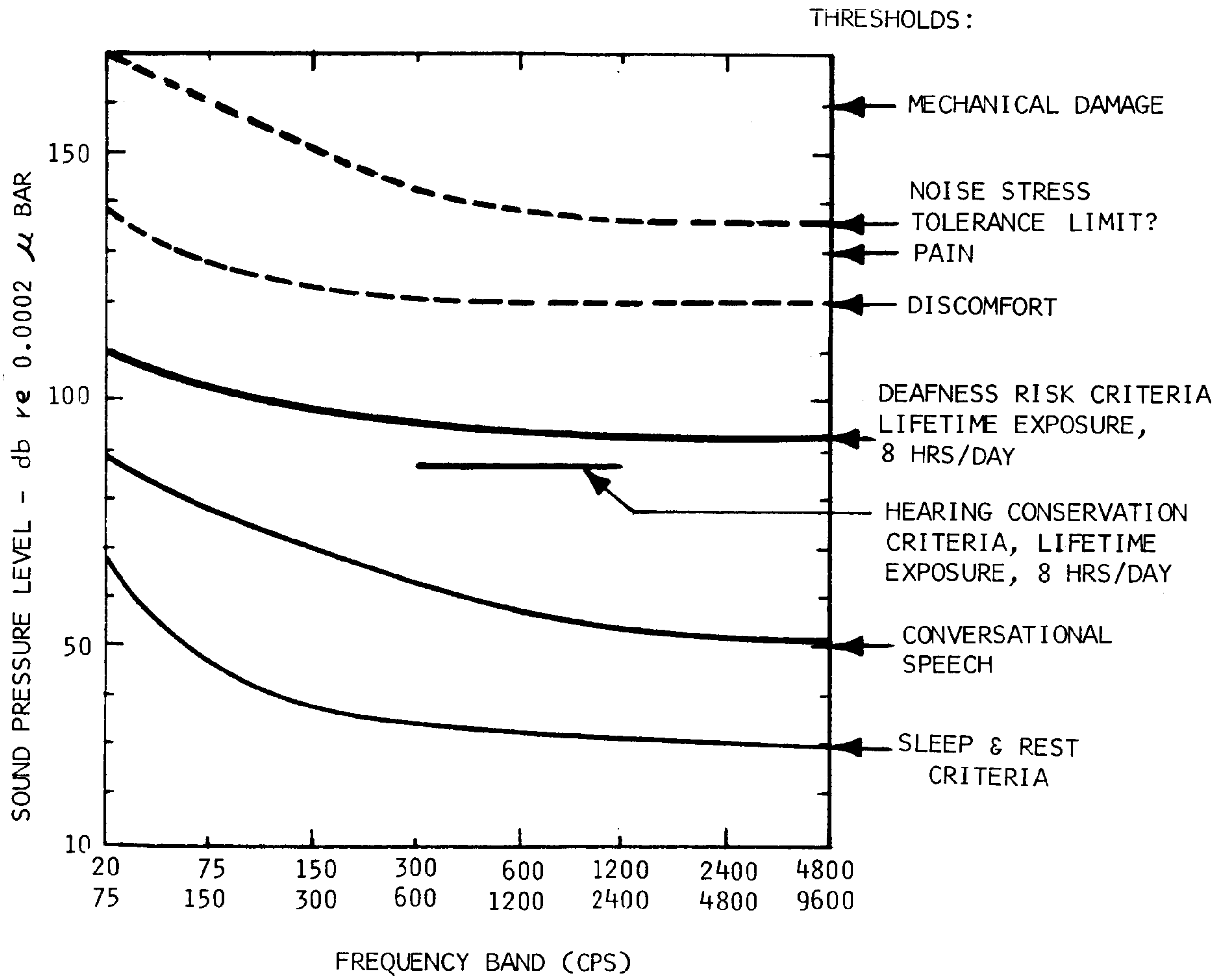
VIBRATION TOLERANCE LIMITS

FIGURE 4.19



EFFECTIVE TEMPERATURE FOR COMFORT REQUIREMENTS

FIGURE 4.20



TOLERANCE CRITERIA FOR NOISE

FIGURE 4.21

REFERENCES FOR SECTION 4

1. Waite, R. E.: Memorandum DB41/005/021. Manned Spacecraft Center, NASA. June 6, 1967.

2. Feddersen, W. E., Doctor: Memorandum EC64-90. Manned Spacecraft Center, NASA. June 8, 1967.

3. Design Standard - 267A; Marshall Space Flight Center. June 31, 1966.

4. Anthropometry of Flying Personnel; WADC Technical Report 52-321. September, 1954.

5. Stone, R. W., Jr., and Piland, W. M.: Factors Related to Weightlessness in Space; a Review of Potential Problems and Prospective Solutions. Langley Working Paper 425.

6. Newsom, B. D. PhD, Shafer, W. A., M. D., and French, R. S. PhD: Adaption to Prolonged Exposure in the Revolving Space Station Simulator. Aerospace Medicine. August, 1966.

5.0 EXPERIMENTS

Human response to artificial gravity offers a parallel to the responses to weightlessness. There are still unanswered questions about the effects of weightlessness on man and many of these are likely to remain unanswered until extended orbital flights are accomplished. An experimental program to obtain comparable data for weightlessness and artificial gravity (.3g acceleration) would do much to establish a firm basis for the safe and effective use of man in long-duration space missions by providing intermediate data points between full Earth gravity and weightlessness. This would also aid in the design of systems to ameliorate the effects of less than Earth gravity upon the human organism and to compensate for human response limitations under less than Earth gravity.

Information on the physiological effects of weightlessness has been obtained from the following sources:

1. Animal and human exposure to very short-term weightlessness in ballistic vehicles, aircraft flying Keplerian trajectories, and drop towers.
2. Short-term orbital space flights.
3. Studies in prolonged bed rest, immobilization, and water immersion (construed as being, in part, physiologically analogous to weightlessness).
4. Reverse extrapolation of data obtained from biological systems exposed to increased "g" forces.
5. Speculation as to the presumed logical consequence of zero gravity exposure upon a number of basic physiological systems because of their gravity dependence.

Very little has been learned about the actual exposure of man to artificial gravity between zero "g" and one "g" because of the difficulty of simulation while on Earth.

5.1 EXPERIMENT DESCRIPTIONS

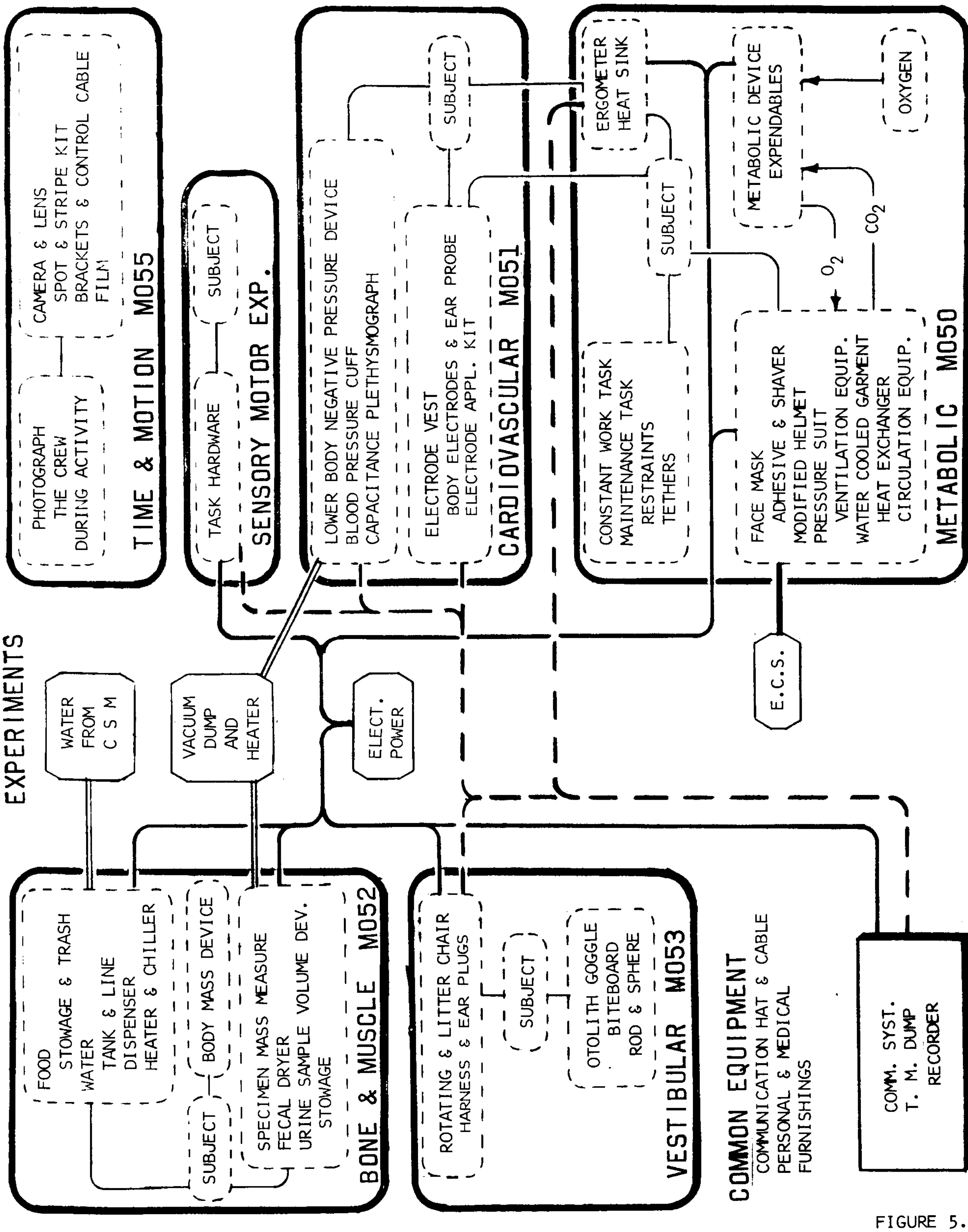
The experiments performed during this mission are to be the same as those performed on the S-IVB Workship mission. These experiments will be performed to obtain comparable circulatory, musculoskeletal, and spatial orientation data at zero "g" and 0.3 "g".

In the following paragraphs, each experiment is described briefly, with the objective identified. Requirements placed on the Experiment Module by the experiments, with reference to power, weight, volume, time and frequency of measurement, are shown in Table 5.1. Other requirements and interfaces are discussed in paragraph 5.3.6. Figure 5.1 presents the experiment interfaces with each other.

EXPERIMENTS	ELECTRIC POWER KW HR.	WEIGHT LBS.	VOLUME FT^3	TIMES PERFORMED	MINUTES EACH TIME	DATA: MANUAL LOG & NOTES	DATA: FILM	DATA: TV-VOICE TRANSMIT	DATA: DATA TRANSMIT
SENSORY MOTOR	0.36	40.0	2.0	14	30	X	X	X	X
METABOLIC COST (M050) A. RESTING AND ERGOMETER (SHARE WITH M051) B. NON-SUITED TASK C. SUITED TASK	1.06 (.22) (.19) (.65)	228.7 (188.3) (26.8) (13.6)	12.0 (4.3) (2.6) (5.1)	 6 6 6	 40 40 40	 X X X	 X X X	 X X X	 X X X
CARDIOVASCULAR (M051) (INCLUDES VECTOCARDIOGRAM - M018)	.57	40.3	4.0	7 14	70 60	X X		X X	X X
BONE AND MUSCLE (M052) (INCLUDES SPECIMEN MASS - M056 AND BODY MASS - M058) *FOOT AND DRINKING WATER FOR CREW IS INCLUDED IN EPS AND CREW SYSTEMS.	2.99	75.5*	16.4	40 20 7	15 20 10	X X X	RETURN	URINE & FECAL X	SAMPLES
VESTIBULAR (M053) A. DYNAMIC B. STATIC (INCLUDES OTOLITH - M009)	.76 (.57) (.19)	113.1 (101.1) (12.0)	5.8 (5.7) (.1)	 8 6	 30 37	 X X		 X X	 X
TIME AND MOTION (M055) *INCLUDES 20 LBS. OF FILM TO BE RECOVERED.	0	22.7*	.8	140	2 AVG	X	X	X	
TOTAL	7.75	520.3	41.0						

EXPERIMENTS SUMMARY

TABLE 5.1



EXPERIMENTS
PHOTOGRAPH THE CREW DURING ACTIVITY
CAMERA & LENS
SPOT & STRIPE KIT
BRACKETS & CONTROL CABLE
FILM
TIME & MOTION M055
TASK HARDWARE
SUBJECT
SENSORY MOTOR EXP.
LOWER BODY NEGATIVE PRESSURE DEVICE
BLOOD PRESSURE CUFF
CAPACITANCE PLETHYSMOGRAPH
SUBJECT
ELECTRODE VEST
BODY ELECTRODES & EAR PROBE
ELECTRODE APPL. KIT
CARDIOVASCULAR M051
ERGOMETER HEAT SINK
SUBJECT
METABOLIC DEVICE EXPENDABLES
OXYGEN
CO_2
O_2
CONSTANT WORK TASK
MAINTENANCE TASK
RESTRAINTS
TETHERS
FACE MASK
ADHESIVE & SHAVER
MODIFIED HELMET
PRESSURE SUIT
VENTILATION EQUIP.
WATER COOLED GARMENT
HEAT EXCHANGER
CIRCULATION EQUIP.
METABOLIC M050
E.C.S.
WATER FROM C S M
VACUUM DUMP AND HEATER
ELECT. POWER
FOOD
STOWAGE & TRASH
WATER
TANK & LINE
DISPENSER
HEATER & CHILLER
BODY MASS DEVICE
SUBJECT
SPECIMEN MASS MEASURE
FECAL DRYER
URINE SAMPLE VOLUME DEV.
STOWAGE
BONE & MUSCLE M052
ROTATING & LITTER CHAIR
HARNESS & EAR PLUGS
SUBJECT
OTOLITH GOGGLE
BITEBOARD
ROD & SPHERE
VESTIBULAR M053
COMMON EQUIPMENT
COMMUNICATION HAT & CABLE
PERSONAL & MEDICAL
FURNISHINGS
COMM. SYST.
T. M. DUMP
RECORDER

FIGURE 5.1

5.1.1 Sensory Motor Performance

Perform physical manipulations to detect changes in performance and thereby determine the relationship between physiological condition and performance. Test to determine vigilance, attention, memory, problem solving, speech-reading-comprehension, and continuous-discrete, gross and fine motor performance. Data will consist of time and sequence measurements.

5.1.2 Metoabolic Cost - M050

Perform calibrated exercises on a "bicycle" ergometer and utilize operational and maintenance task boards in the suited and non-suited mode to determine:

a. Changes in man's metabolic effectiveness.
b. The metabolic cost of activities as compared to their cost on Earth.
c. The difference in metabolic cost of work between suited and non-suited modes; also evaluate ground based reduced-gravity simulators and the benefits of the "bicycle" ergometer.

Measure oxygen consumption before, during and after specified tasks. The data will include measurement of heart rate, respiration, body temperature, ergometer output, ergometer rpm, metabolic device out-put, voice, identification, and time.

5.1.3 Cardiovascular Function - M051

Lower Body Negative Pressure testing will be performed to determine the course of cardiovascular deconditioning. This will provide insight into the following questions: Is there progressive cardiovascular deterioration? If so, is it uniform or sporadic? At what level must it be checked? How may such deterioration be checked? Can preconditioning minimize inflight effects? What are the effects of artificial gravity and crew exercise? Test for changes in orthostatic response, i.e., cardioacceleration, lower extremity pooling of blood, and decresed pulse pressure. The Vector-cardiogram experiment (M018) is included as a part of this experiment.

Data will include measurement of chest and side electrode outputs for cardiogram, and measurement of heart rate, lower body negative pressure device, blood pressure, body temperature, time and voice comments.

5.1.3.1 Vectorcardiogram - M018

Utilize the vectorcardiogram to detect changes in the electrical activity of the heart, and to correlate the changes observed during (and immediately after) space flight with anatomical shifts in heart position and of body fluids, changes in heart size, altered myocardial perfusion and other alteration in cardiac function, and also to apply computer techniques to the data analysis. Test before, during, and after a three minute period of exercises. "At rest" measurements of the man in the CSM can be obtained if a longer harness or CSM plug-in is made available.

5.1.4 Bone and Muscle Changes - M052

Observe and record food intake and waste output, and collect waste samples for post-flight analysis. Data will be used to determine musculoskeletal status and to evaluate water, electrolyte and possibly steroid changes. Results will be compared with other calcium and nitrogen balance studies. Use the Body Mass Measuring Device (M058) and the Specimen Mass Measuring Device (M056) as part of this experiment. The man in the CSM will perform this experiment except for the Body Mass Measurement (M058). Data will consist of hand-logged record of food and water intake, and urine and fecal outputs. Urine and fecal samples will be collected.

5.1.4.1 Specimen Mass Measurement Device - M056

Measure the mass of the astronaut's waste to support the Bone and Muscle Experiment (M052). Utilize calibrated masses to check validity and behavior of the device.

5.1.4.2 Body Mass Measurement Device - M058

Measure the astronaut's body mass to support the Bone and Muscle Experiment (M052). Utilize known masses to check validity and behavior of the device.

5.1.5 Vestibular Function - M053

Report visual and other sensations to determine the effect of artificial gravity on the semicircular canal and gravity receptor activity and evaluate the effect of changes on the astronaut's ability to judge spatial localization. Test in rotating chair and on tilting litter. Include the Otolith Goggle Experiment (M009) as a part of this experiment. Data will include chair position and angular velocity and crew comments to a list of questions.

5.1.5.1 Otolith Function - M009

Perform adjustment of optical device to orient dot-line relative to eye and thereby explore the effects of exposure to artificial gravity upon otolith activity as it is reflected in reflex ocular movement and visual orientation. Test to measure ocular counterrolling. Include as part of the Vestibular Experiment

(M053) on days when it is performed. The man in the CSM will perform this experiment. Data will consist of noting position settings on the goggle.

5.1.6 Time and Motion Study - M055

Photograph the crew's activities while they are performing operational and experimental tasks to evaluate the relative consistency between ground-based and in-flight task performance. Data will consist of manually logging the operation being filmed, the time and film sequence.

If sufficient communication capability exists to permit live TV transmission, the ground-based analysts may be able to modify the performance of the experiment in flight. This would make it possible to have good correlation of the data from this flight with the S-IVB Workshop mission. Alternately, additional procedures might be tried to determine if they would be beneficial.

5.2 DATA MANAGEMENT

Data management will be handled by the communications system. The Data Management Subsystem will accept signals directly from the experiment sensors and condtions, amplify, or modify those signals for transmission to a ground station. The signal from several of the sensors will be fed back to provide an onboard display of heart rate, blood pressure, and body temperature. Included in the Data Management subsystem is a recorder which will hold the data output until such time as it can be dumped to a ground station.

In addition to the verbal comments of the crew which are fed to the Data Management System, the crew will manually log notes and data. The log and also photographic film will be recovered.

5.3 IMPACT OF EXPERIMENTS ON SPACECRAFT SYSTEMS

The impact of the experiments on the Electrical Power System is probably best shown by the power profile (Figure 6.4) which illustrates the power requirements and variations throughout the mission.

The Environmental Control System, in addition to providing normal cabin environment, will provide oxygen for the pressure suit at 3.7 psi above cabin pressure. Cooling water circulation and heat rejection equipment required for a crewman to utilize the water cooled garment will be provided. A source of vacuum will be made available for the Lower Body Negative Pressure Device, the Fecal Dryer and for urine dump.

Crew Systems will provide food for the crewmen. The diet will be selected to be compatible with the Bone and Muscle experiment. The astronauts will transfer drinking water from the CSM fuel cells in "batches" as needed. Crew Systems will also provide common equipment such as handholds, tethers, restraints, clocks, lights, seats, bunks, work shelves, waste management and personal and medical kits.

The material to be recovered from the Experiment Module for further analysis on the ground will, of course, include the manual notes and daily log as well as the experiment data and samples. Urine samples (100-200 cc/day) and seven days of fecal samples will be returned. The remaining data (about 10 pounds) to be returned will be in the form of magnetic tapes and photographic film.

5.4 EXPERIMENT SCHEDULING

Figure 5.2 illustrates experiment scheduling for the ten day baseline mission. The frequencies shown are sufficient to satisfy all known requirements for experimental data. Crewmen A and B are stationed in the EM during the artificial gravity portion of the mission(days 3-9) and crewman C remains in the CM during the entire mission.

Present operational ground rules require at least one man in the CM at all times. The desired $\pm$ 0.01g tolerance on the test subjects would be exceeded if A or B replaced C in the CM. Since some of the experiment apparatus cannot readily be moved to the CM, several experiments are performed on A and B only.

To investigate the feasibility of actually achieving the schedule presented in Figure 5.2, a typical crew task timeline was constructed (Figure 5.3).

The fifth and sixth days were selected as pepresentative of the heaviest experiment work load to be accomplished during the mission.

AAP scheduling constraints were adopted as follows:

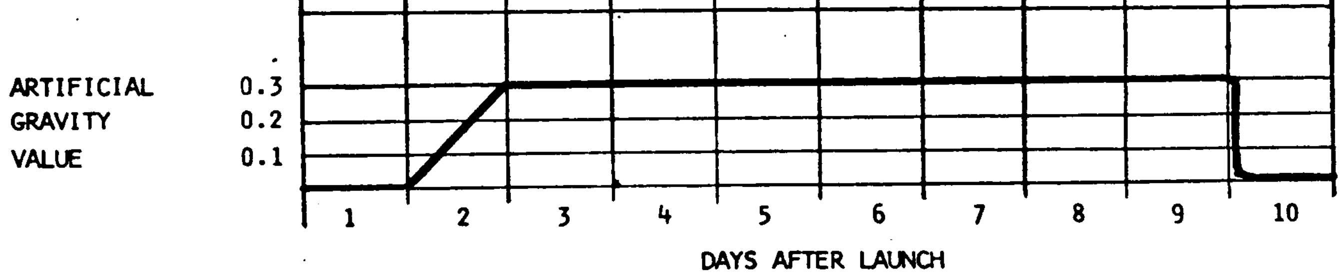
Sleep - 8 hours/day
Meals - 3 one-hour periods/day
Housekeeping - $1\frac{1}{2}$ hours/day
Systems housekeeping - 2 hours/day

It is clear from Figure 5.3 that very little free time is available for crewmen A and B if the desired experiment schedule is maintained. Crewman C has some 9 hours of free time per day as a result of his nonparticipation in several of the experiments, but the ground rules prevent effective utilization of this time.

EXPERIMENT:

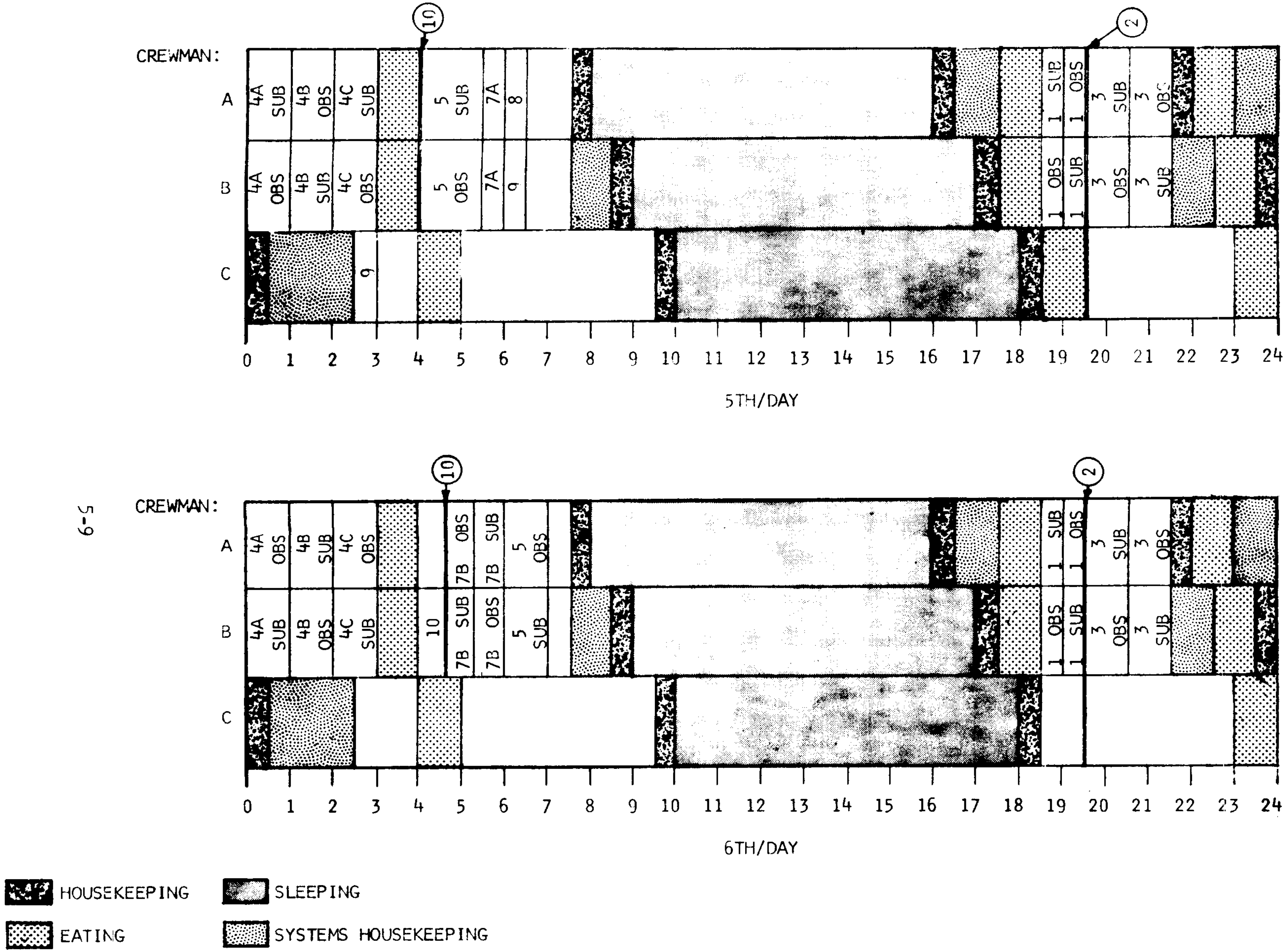
1 SENSORY MOTOR
2 OTOLITH (M009)
3 VECTORCARDIOGRAM (M018)
4 METABOLIC COST (M050)
   A ERGOMETER
   B UNSUITED TASK
   C SUITED TASK
5 CARDIOVASCULAR (M051)
6 BONE - MUSCLE (M052)
7 VESTIBULAR (M053)
   A DYNAMIC
   B STATIC
8 TIME & MOTION (M055)
9 SPECIMEN MASS (M056)
10 BODY MASS (M058)

SUBJECT:	1	2	3	4	5	6	7	8	9	10
1			AB	AB	AB	AB	AB	AB	AB	
2	ABC	ABC	ABC	ABC	ABC	ABC	ABC	ABC	ABC	
3			AB	AB	AB	AB	AB	AB	AB	
4A			A	B	A	B	A	B		
4B			B	A	B	A	B	A		
4C				B	A	B	A	B	A	
5			A	B	A	B	A	B	A	
6	ABC	ABC	ABC	ABC	ABC	ABC	ABC	ABC	ABC	ABC
7A			AB		AB		AB		AB	
7B				AB		AB		AB		
8	A		B		A		B		A	
9	BC		AC		BC			AC		BC
10			AB	AB	AB	AB	AB	AB	AB	



CREW EXPERIMENT ALLOCATIONS

FIGURE 5.2



NOTE: EXPERIMENT 6 IS INCLUDED IN EATING AND HOUSEKEEPING TIMES.

MISSION PROFILE

FIGURE 5.3

6.0 SUBSYSTEMS

The basic ground rules of utilizing existing systems and creating minimum impact on the CSM have been followed during the subsystems study. The interface with the command module shown on Figure 6.1 has been kept to a minimum, and utilizes the existing umbilicals for Electrical Power, Instrumentation, Controls, Caution and Warning Systems. The Stabilization and Control Panel is a "carry through" item as is the connection for the Oxygen System. Table 6.1 shows the modifications required for the CSM with those subsystems.

The interface between the subsystems is indicated on Figure 6.2. These will be built into the Experiment Module and should be reasonably simple.

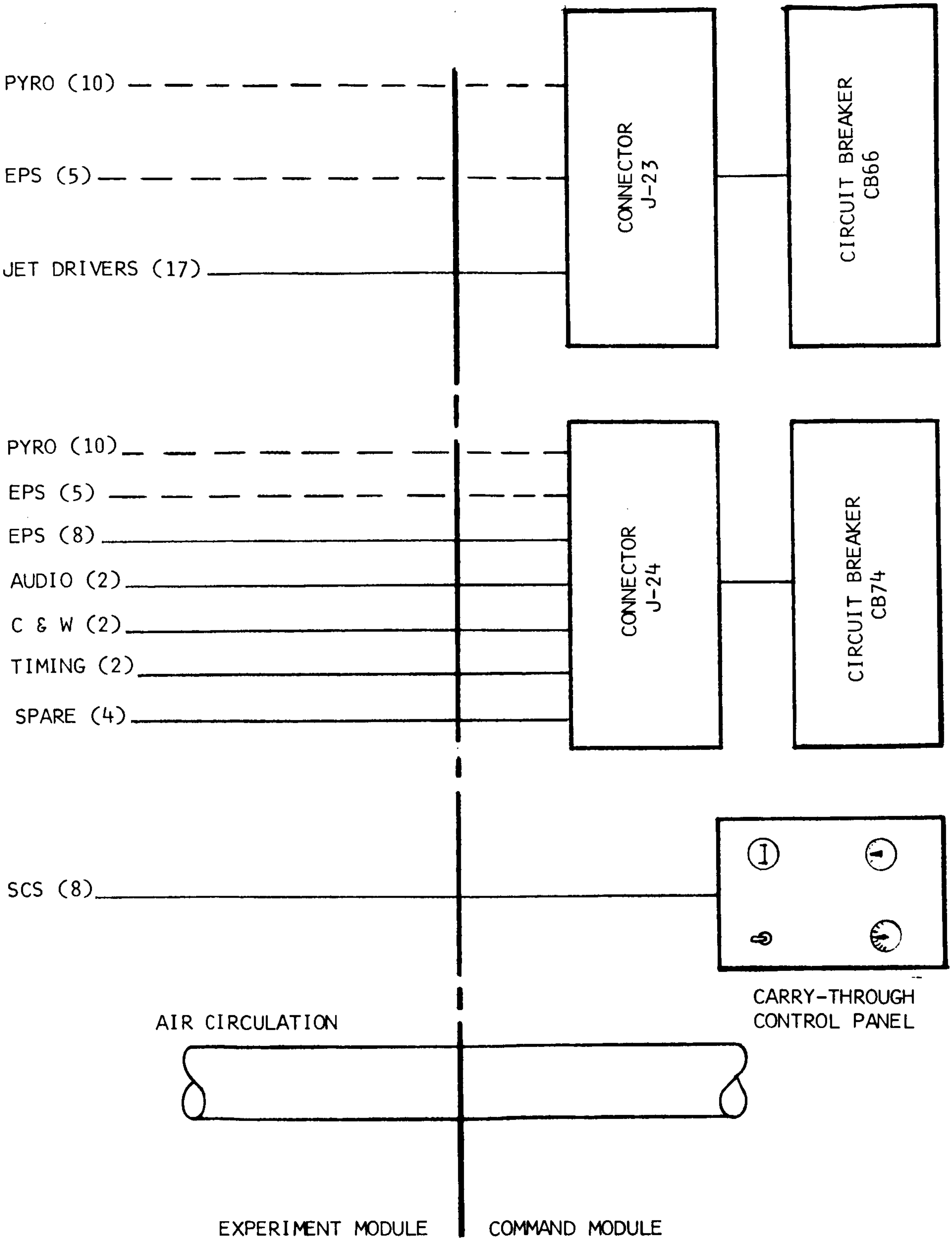
6.1 ELECTRICAL POWER SYSTEM

The Electrical Power System provides an average of .72 KW (.30 KW to 1.09 KW) to the electrical equipment in the Experiment Module. Standard Apollo electrical power equipment is utilized except that modification of the battery charger may be necessary since it was not required to recharge the batteries as quickly nor as often as is now needed. Two Apollo entry batteries provide 2.4 KWH for emergency and peak loads. In the partially discharged condition which can occur from providing makeup power for peak loads, the batteries still retain sufficient capacity for operation of the Experiment Module at emergency power for approximately 2½ hours. Fuel cells in the CSM provide the normal Experiment Module power plus battery charging power requirements through an umbilical to the Experiment Module. The significance of utilizing the CSM fuel cells system for power is recognized when a battery power system versus mission length study is accomplished.

6.1.1 Battery/Mission Length Tradeoff

The limited payload available for this mission compels maximum utilization of excess electrical power available from the CM. Figure 6.3 graphically illustrates the mission length versus power problem. Plotting EM energy requirements with excess CSM energy as limited by cryogenic storage capacity, the curves intersect at 10.6 days. Thus, missions up to 10.6 days could be flown without supplementary primary batteries in the EM. Since battery weight becomes prohibitive for missions significantly longer than this, a baseline mission length of 10 days has been adopted for this study.

The capacity of the CM/LM power umbilical in the Block II CSM is not sufficient for the power levels required in the EM. Modification of the CM, including additional conductors and larger circuit breakers, will be necessary to avoid primary batteries in the EM.



CM/EM INTERFACES

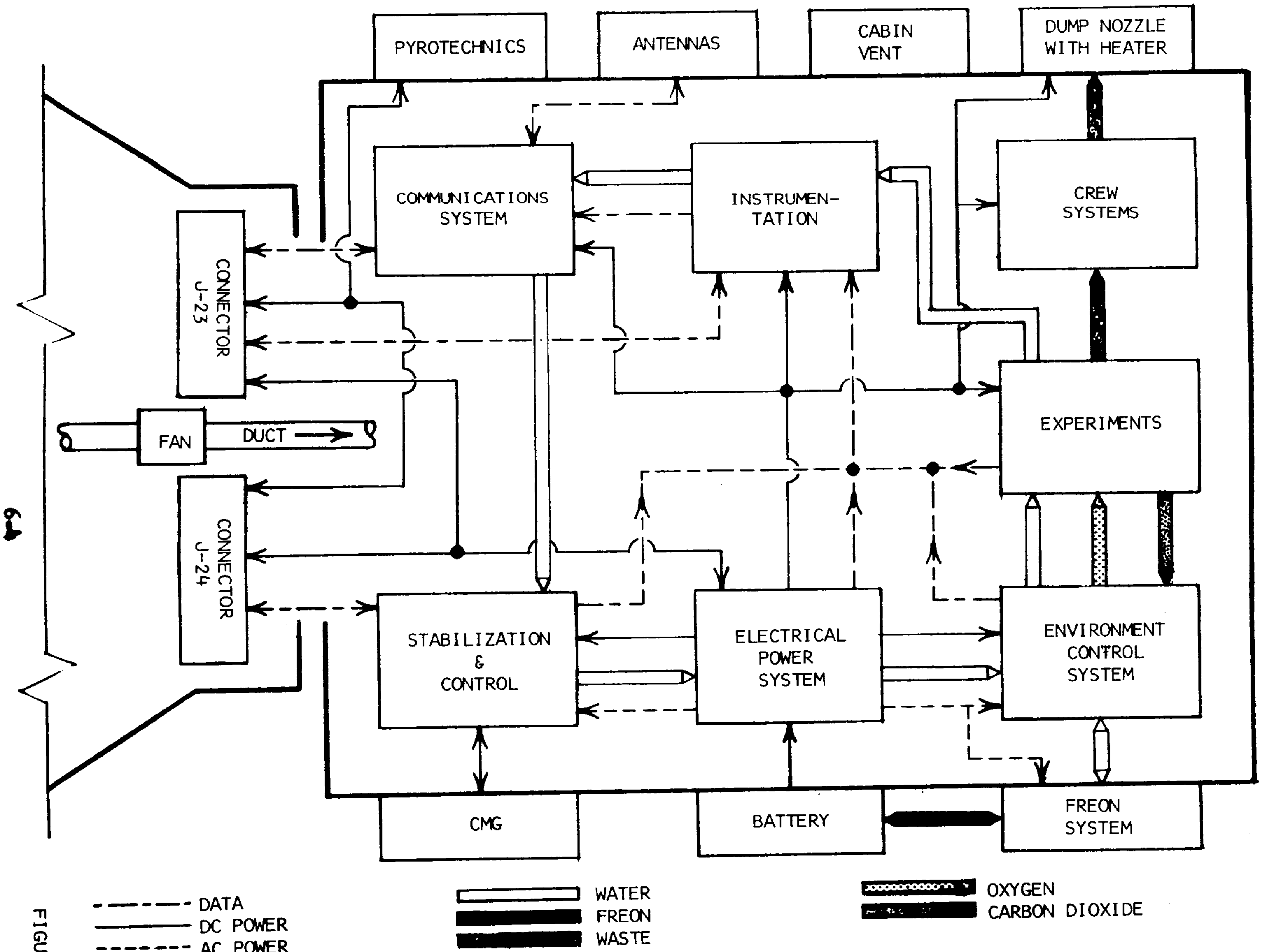
FIGURE 6.1

CSM MODIFICATIONS

- NEW C/B FOR EPS UMBILICAL
- ADDITIONAL EPS UMBILICAL CONDUCTORS
- CIRCULATION FAN PROVISIONS*
- COMPUTER PROGRAMMING CHANGES
- RCS JET DRIVER CONTROL FROM EM*
- C & W INTERFACE*
- AUDIO HARDLINE*
- ANTENNA COUPLING (POSSIBLE)*
- LONGER SUIT UMBILICAL (?)*
- HAND HOLDS AND STEPS IN TUNNEL (?)
- MORE ACCURATE DOCKING INDEXING PROVISIONS (?)*

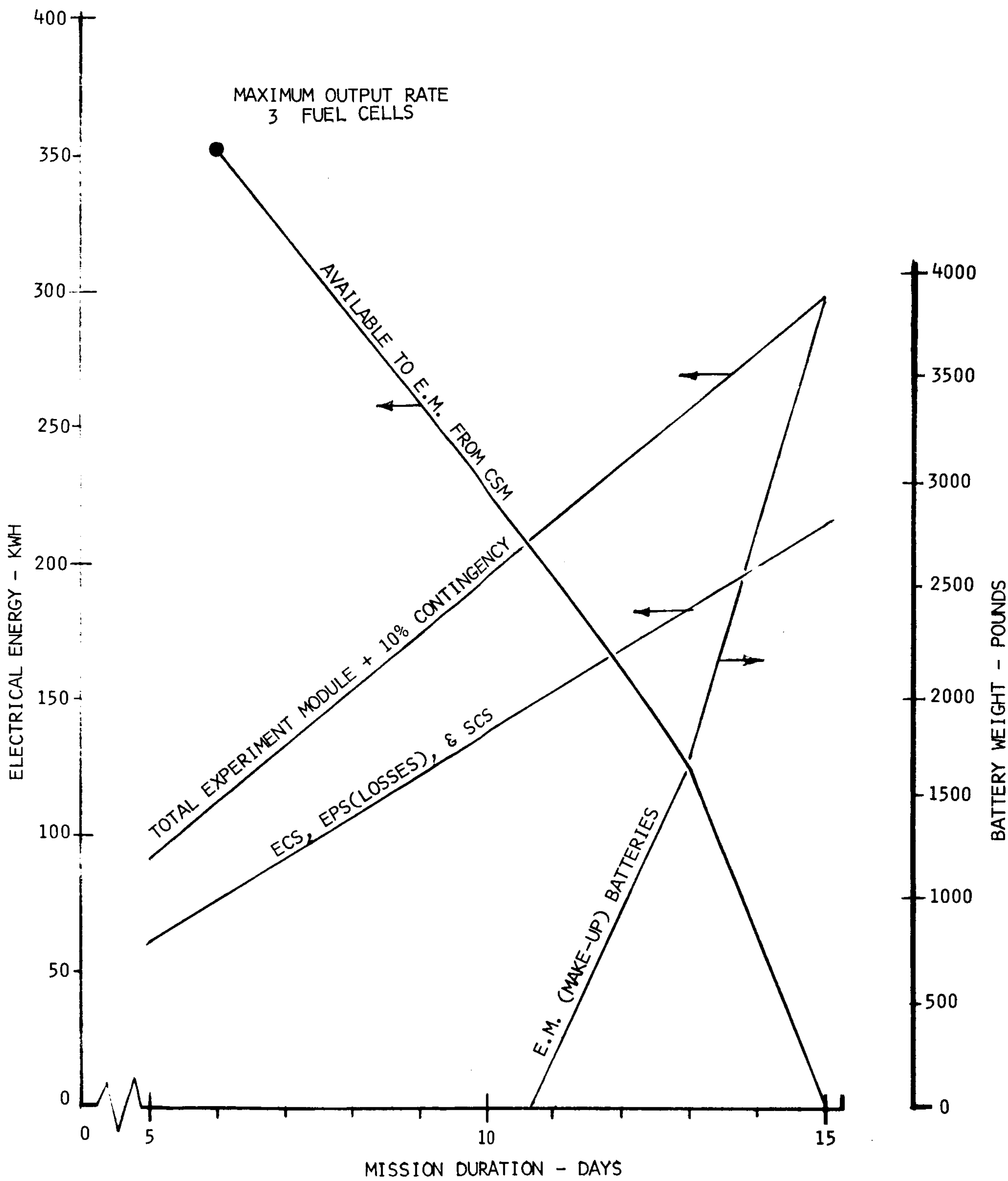
* REQUIRED FOR 1A MISSION

TABLE 6.1



EXPERIMENT MODULE SYSTEM INTERFACES

FIGURE 6.2



BATTERY / MISSION LENGTH TRADEOFF

FIGURE 6.3

6.1.2 Electrical Power Profile

The profile shown on Figure 6.4 shows the variations in electrical power used in the Experiment Module as a function of mission time. The heavy line divides those systems that have generally stable a.c. power requirements (below the line), and those experiments and subsystems that require predominantly d.c. power. Experiments are planned for the time during which the two crewmen in the Experiment Module are being subjected to the .3 g acceleration (third day through ninth day). The communications, instrumentation, and lighting power requirements are determined largely by the crew's activities; whether awake and active or asleep. Electrical power for the Stabilization and Control System is generally stable throughout the active period (second day through ninth day), after the seven hour control moment gyro run-up at the end of the first day. The power requirement for ECS and EPS losses is stable for the entire mission.

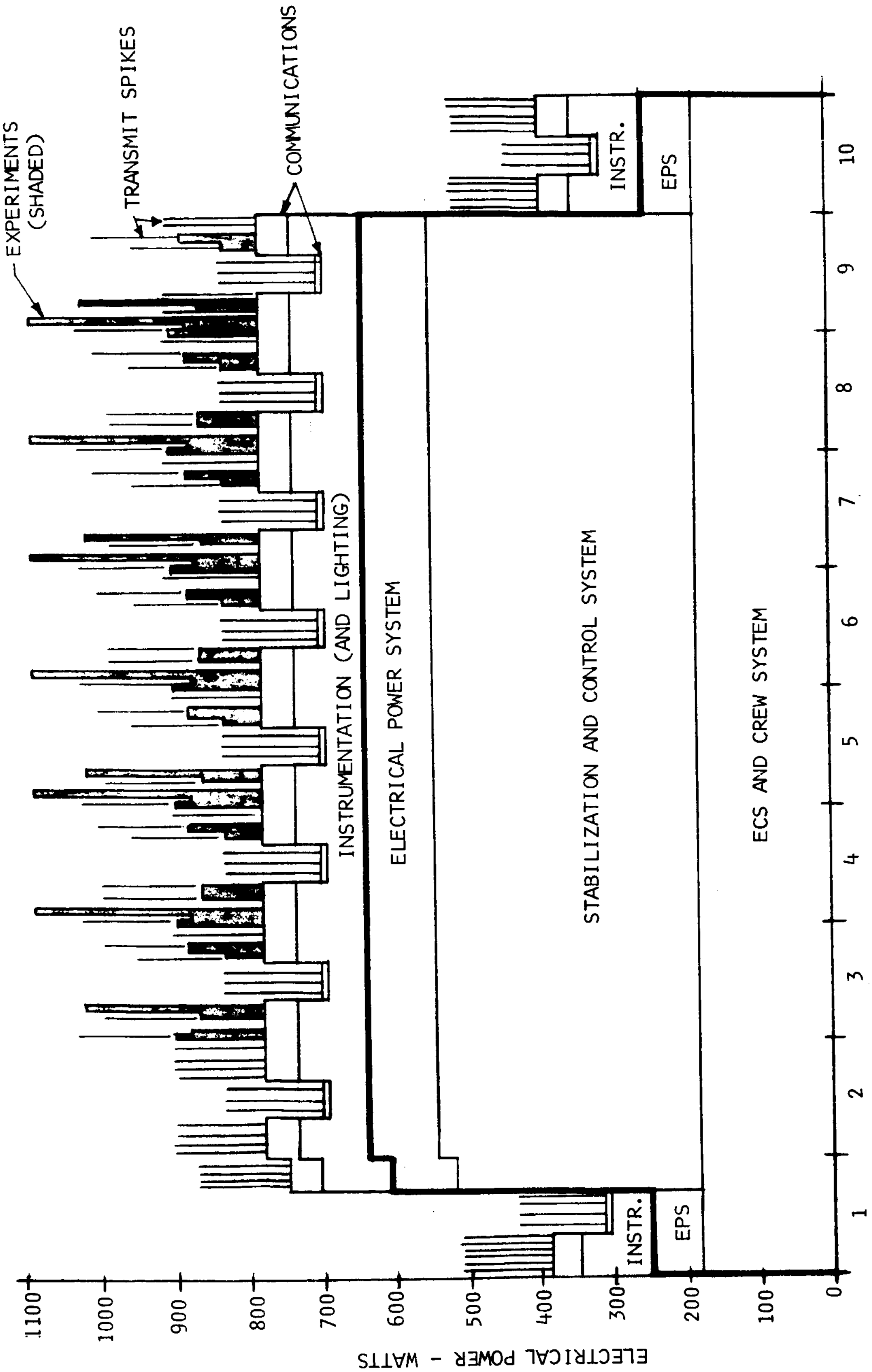
6.1.3 Electrical Power Distribution Systems

Figure 6.5 is a schematic of the distribution system for the artificial gravity station. Electrical power for the Experiment Module is generated by fuel cells in the CSM. This power is picked up at a circuit breaker off the CM Main Bus and routed through the CM/EM umbilical, with reverse current protection, to the EM DC Bus. The experiments and equipment requiring DC power are connected through circuit breakers to the DC Bus. A 1250 VA inverter is powered from the DC Bus and supplies 400 cycle AC through voltage, current and frequency regulators to the equipment requiring AC power. A redundant inverter and control is provided. A battery charging circuit maintains the two batteries at full charge. All equipment that is required during an emergency is powered by DC from the DC Bus.

6.2 ENVIRONMENTAL CONTROL SYSTEM

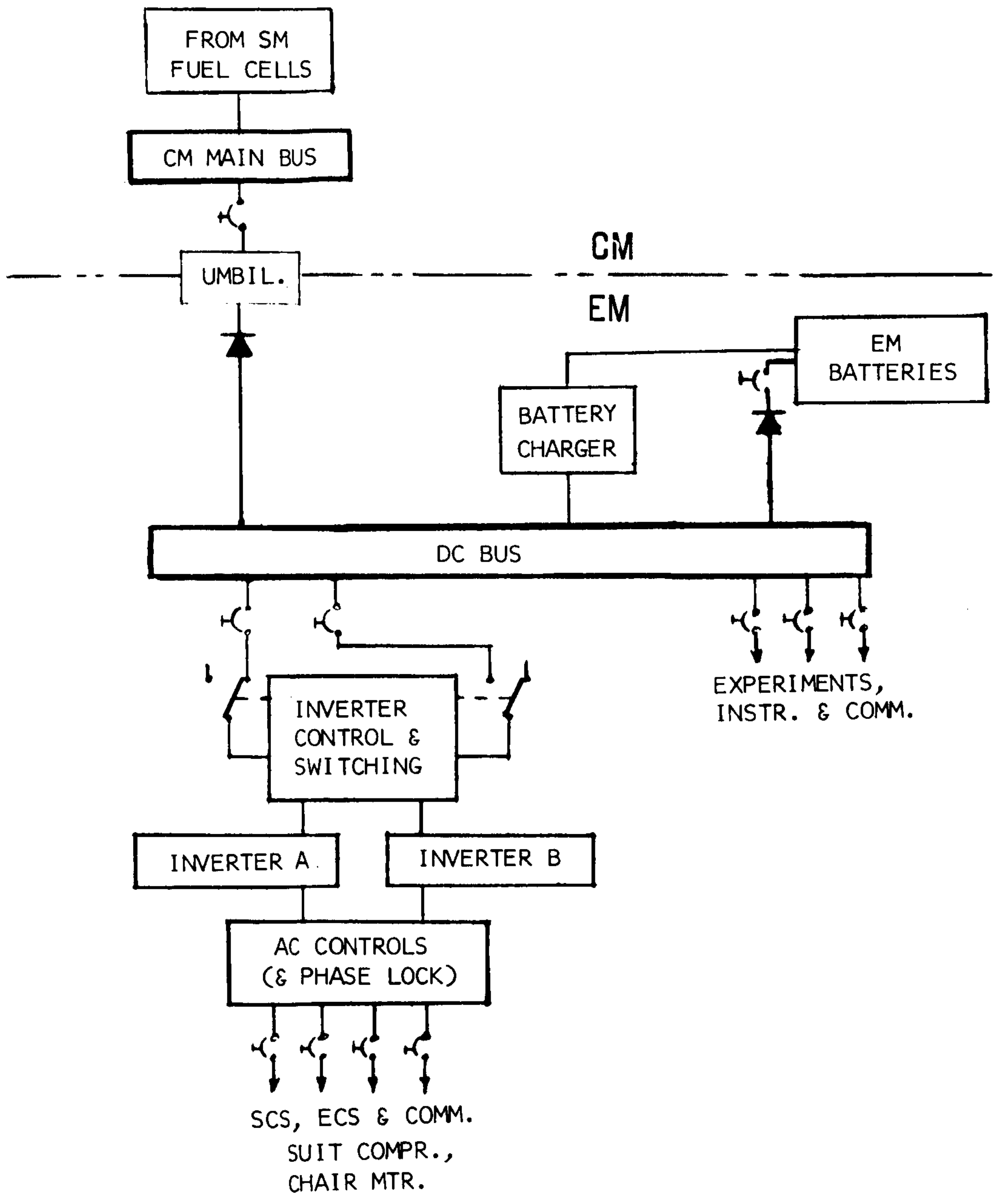
The environmental control and life support system (EC/LSS) is designed to provide the EM flight crew with a conditioned environment that is both life-supporting and as comfortable as possible. The EC/LSS design includes an interface with the command module electrical power system, which supplies oxygen for pressurization, and potable water for crew use. It also interfaces with the electronics equipment in the EM, for which the EC/LSS provides thermal control; and with the experiments to be conducted in the EM. Figure 6.6 shows a schematic of the EC/LSS, while Table 6.2 presents a list of required items of equipment.

The EM EC/LSS is put into operation by the crew after CM-EM docking and crew transfer. During this operating period the system provides the following four major functions for the crew:



EXPERIMENT MODULE POWER PROFILE

FIGURE 6.4



POWER DISTRIBUTION

FIGURE 6.5

EXPERIMENT MODULE

ENVIRONMENTAL CONTROL/LIFE SUPPORT SYSTEM

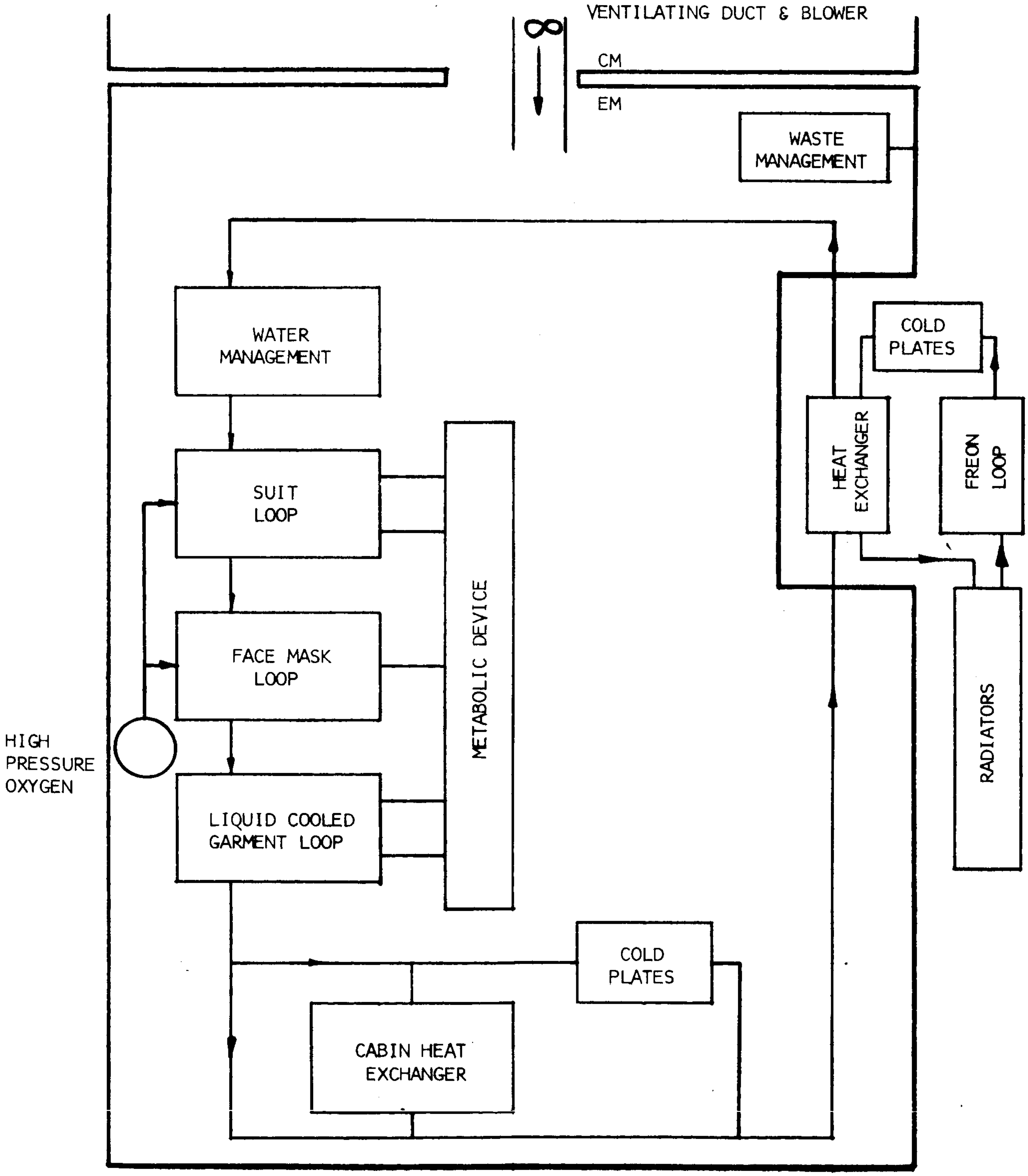


FIGURE 6.6

ENVIRONMENTAL CONTROL SYSTEM EQUIPMENT

	ATMOSPHERE PURIFICATION AND SUIT LOOP
1.1	EM VENTILATING BLOWER
1.2	EM-CM DUCT
1.3	SUIT COMPRESSOR
1.4	SUIT HEAT EXCHANGER ASSEMBLY
1.5	FACE MASK O_2 HEAT EXCHANGER
	THERMAL CONTROL
2.1	RADIATOR (FREON LOOP)
2.2	COOLANT LOOP HEAT EXCHANGER
2.3	COOLANT LOOP CHECK VALVE
2.4	COOLANT PUMP ASSEMBLY
2.5	COOLANT FILL CONNECTION
2.6	COOLANT MANUAL DIVERTER VALVE
2.7	COOLANT SHUTOFF VALVE
2.8	LIQUID COOLED GARMENT HEAT EXCHANGER
2.9	LIQUID COOLED GARMENT PUMP
2.10	FREON PUMP ASSEMBLY
2.11	FREON FILL CONNECTION
2.12	CABIN TEMPERATURE CONTROL VALVE
2.13	LIQUID COOLED GARMENT
2.14	COLD PLATES
	ATMOSPHERE CONDITIONING
3.1	TEMPERATURE SELECTOR
3.2	CABIN TEMPERATURE ANTICIPATOR
3.3	TEMPERATURE CONTROL
3.4	CABIN TEMPERATURE SENSOR
3.5	CABIN HEAT EXCHANGER
3.6	CABIN HEATER
3.7	CABIN FAN
3.8	CABIN PRESSURE RELIEF VALVE
	SUIT LOOP OXYGEN SUPPLY
4.1	OXYGEN TANK
4.2	OXYGEN DEMAND PRESSURE REGULATOR
4.3	MANUAL METERING VALVE
4.4	EMERGENCY INFLOW CONTROL VALVE
4.5	PRESSURE REGULATOR ASSEMBLY
4.6	SHUTOFF VALVE
	WATER MANAGEMENT
5.1	POTABLE WATER TANK
5.2	WATER CHILLER
5.3	WATER CHECK VALVE
5.4	WATER SHUTOFF VALVE

TABLE 6.2

WATER MANAGEMENT (CONTINUED)

5.5 POTABLE WATER SUPPLY SUBASSEMBLY
5.6 TANK PRESSURE REGULATOR AND RELIEF VALVE
5.7 WATER SHUTOFF VALVE

WASTE MANAGEMENT

6.1 FECAL DRYER
6.2 URINE NOZZLE HEATER
6.3 FECAL CANISTER AND HOSE
6.4 URINAL AND HOSE

INSTRUMENTATION

7.1 SUIT SUPPLY PRESSURE TRANSDUCER
7.2 SUIT COMPRESSOR DIFFERENTIAL PRESSURE TRANSDUCER
7.3 SUIT SUPPLY O_2 TEMPERATURE SENSOR

8.1 COOLANT PUMP PRESSURE TRANSDUCER
8.2 COOLANT TEMPERATURE SENSOR

9.1 OXYGEN SUPPLY PRESSURE TRANSDUCER
9.2 CABIN TEMPERATURE SENSOR

10.1 CABIN PRESSURE TRANSDUCER

11.1 CO_2 PARTIAL PRESSURE SENSOR

- Atmosphere Control
- Water Management Control
- Thermal Control
- Waste Management Control

The function of the EM atmosphere control is to regulate the pressure and temperature of the cabin and suit gases; maintain the desired humidity by removing excess water from the suit and cabin gases; and control the level of contamination of the gases by removing CO_2, odors, and particulate matter. (There are also provisions for supplying oxygen to the metabolic device and for emergency pressurization of the EM when the CM-EM interconnecting hatch is closed.)

The function of the water management control is to store the potable water produced in the fuel cells, and deliver chilled and heated water to the crew for metabolic consumption and hygienic purposes.

The function of the thermal control is to remove excess heat generated by the crew and the spacecraft equipment, and reject unwanted heat to space.

The function of the waste management control is to store and/or dispose of waste solids, liquids, and gases.

Five subsystems operating in conjunction with each other provide the required functions:

Oxygen Subsystem
Pressure Suit Circuit(PSC)
Potable Water Subsystem
Cooling Water Subsystem
Freon Subsystem

The oxygen subsystem controls the flow of oxygen between the command module and the experiment module; controls the flow of oxygen within the experiment module; stores a supply of oxygen for use in experiments and emergencies; regulates the pressure of oxygen supplied to the subsystem and modes; and controls pressure in the potable water tank.

The pressure suit circuit provides one crewmember with a continuously conditioned atmosphere. It automatically controls suit gas circulation, pressure, and temperature; and removes excess moisture from the suit gases. The EM atmospheric humidity and CO_2 levels are controlled by the command module pressure suit circuit.

The potable water subsystem stores potable water; and delivers hot and cold water to the crew for metabolic and hygienic purposes.

The cooling water subsystem provides cooling for the PSC, the liquid cooled garment, the potable water chiller, and the EM equipment; and heating or cooling for the cabin atmosphere.

The freon subsystem radiates to space the excess heat picked up by the cooling water subsystem.

6.2.1 Functional Description

Once in operation, the environmental control and life support system operates continuously throughout all docked mission phases. Control begins after initial docking and crew transfer and continues until EM-CM separation. The following paragraphs describe the operating modes and the operational characteristics of the EC/LSS from the time of launch to EM-CM separation.

6.2.2 EM Atmospheric Control

At launch, the experiment module is purged and pressurized with pure oxygen at atmospheric pressure. After launch and during the ascent, the cabin remains at sea level pressure until the ambient pressure decreases to 6 psi. At that point the cabin pressure relief valve vents the excess gas overboard, maintaining cabin pressure at 6 psi above ambient.

After attaining orbit, leakage will cause the cabin pressure to decrease from 6 psi. After docking, the command module crew can open the interconnecting hatch, install the CM-EM retractable duct, and turn on the intermodule fan. Circulation of the atmosphere insures provision of metabolic oxygen from the normal CSM source and also maintains EM cabin pressure. Should it become necessary for the crew in the experiment module to close the interconnecting hatch, the high pressure oxygen supply will maintain the experiment module pressure for a short time.

The CO_2, odors, and humidity which contaminate the experiment module cabin atmosphere are removed by circulation back to the command module environmental control system.

The PSC in the experiment module is for use by one crewmember during experiment periods and is sufficient for use by two men only during an emergency.

6.2.3 Water Management

In preparing the experiment module for the mission the potable water tank is partially filled to ensure an adequate supply for the early stages of the mission. During operation, the potable water supply is replenished as required from the command module potable water supply. A portion of the water is chilled and made available to the EM crew through the drinking fixture and the food preparation unit. The remainder is heated, and is delivered through a separate valve on the food preparation unit.

6.2.4 Thermal Control

Thermal control is provided by a water coolant loop and a freon heat rejection loop. The cold water is circulated through the water chiller, suit heat exchanger, liquid-cooled garment heat exchanger, face mask O_2 heat exchanger cold plates, cabin heat exchanger, and the coolant loop heat exchanger. The freon loop rejects the excess heat to space through a radiator.

6.2.5 Waste Management

The waste management system requirements are: contain, dry, and store feces; collect, allow sampling, and overboard dump of urine; and remove odor and loose debris. Except for the odor removal and air cleaning operations, these are accomplished manually by the crewmen.

6.2.6 Experiment Impact on EC/LSS

6.2.6.1 Metabolic Cost of Inflight Tasks - M050

1. Engineering Information

a. Metabolic Device and Associated Equipment

Equipment is required to measure oxygen consumption during both rest and exercise periods. Since the respiratory quotient may change during the exercise periods, the device will also permit calculation of R. Q. An additional restraint is the fact that it must measure metabolic rate during unsuited and pressurized suit modes with possible different atmospheres in each.

Although the exact configuration of this device is not known at this time, the following general specifications are being sought: The device will be approximately 2 cubic feet in size and will remain inside the stowage container when in use. The entire container is to be attached to the Experiment Module wall in the experiment area. An electrical umbilical will be attached from the metabolic device to the experiment data system (EDS) during experimental periods. Two respiratory hoses (inspired and expired) will be attached to the front of the metabolic device and to the subject's face mask (through modified helmet during suited operation). During suited operation an additional hose will interface from the metabolic device to the pressure suit for a pressure reference. This connection will probably be with the suit ventilation hoses.

b. Bicycle Ergometer
In order to have a well-calibrated work load, a bicycle ergometer is required. The heat sink for the ergometer may mount separately depending upon heat dissipation sources near the experimental area.

2. EC/LSS Interface Requirements
   a. High pressure oxygen source
   b. Cooling water loop for liquid cooled under garment.

6.2.6.2 Inflight Assessment of Cardiovascular Function - M051

1. Engineering Information
   a. Lower Body Negative Pressure Device (LBNP)
   The device consists of a bag surrounding a framework which may be collapsed for storage, a sealing membrane to fit about the midsection of a man, an evacuation device(to create the required pressure gradient) with suitable controls, valves, and safety devices. A pressure sensor is incorporated to provide recording of tape and an onboard readout of the negative pressure.

2. EC/LSS Interface Requirements
   a. Vacuum Line to LBNP Device

6.2.6.3 Bone and Muscle Changes During Prolonged Spaceflight - M052

1. Engineering Information
   a. Inflight Urine
   Engineering constraints may not permit all micturitions to be collected; therefore, the urine collection system will consider a means of measuring the total 24-hour voidings of each subject, and collecting a minimum aliquot of each void or 24-hour pool. Provisions will be made for identifying the astronaut and time of micturition. Two to four sample bags per man per day will be stowed onboard unless experience and stowage constraints dictate otherwise.
   b. Inflight Stools
   While in the EM the wet and dry weight of stools will be determined by mass measurement for a minimum seven-day period. The containers will be labeled for terrestrial return at the termination of the mission. Otherwise the mass of all stool specimens in the CM and EM will be measured and recorded, but need not be returned for postflight analyses.
   c. Inflight Water
   The water measuring devices (WMD) for drinking and food reconstitution will be utilized and consumption by each crewmember recorded.
   d. The Inflight Diet
   The inflight diet will be the Apollo type menu of freeze dehydrated and otherwise dried or processed

foods of known composition. A record of food consumed will be maintained.

2. EC/LSS Interface Requirements
   a. Provisions for urine collection, dump, and sample storage.
   b. Provisions for fecal collection, drying, and sample storage.
   c. Accurate measuring of water consumed by each crew member.
   d. Accurate measuring of food consumed by each crew member.

6.2.7 Experiment Module (EM) Impact on EC/LSS

6.2.7.1 Cabin Atmosphere

1. Engineering Information
   The EM will require a conditioned atmosphere that is both life supporting and as comfortable as possible for the crew. The EM atmosphere will require pressure, temperature, humidity, and contamination (CO_2, odors, and particulate matter) control.

2. EC/LSS Interface Requirements
   a. Oxygen supply.
   b. Cabin atmosphere pressure control.
   c. Cabin atmosphere temperature control.
   d. Cabin atmosphere humidity control.
   e. Cabin atmosphere contamination control.

6.2.7.2 Water Management

1. Engineering Information
   The EM will require a water management system capable of supplying hot (154° F. nominal) and cold (50° F. nominal) potable water to the two crewmen for food preparation and drinking.

2. EC/LSS Interface Requirements
   a. Potable water supply.
   b. Heat and heat sink source to heat and chill water.

6.2.7.3 Food

1. Engineering Information
   A balanced diet will be furnished to each crewmember.

2. EC/LSS Interface Requirements
   a. Food storage.
   b. Food preparation equipment.

6.2.7.4 Waste Management

1. Engineering Information
   The EM will require a waste management system to control, and collect or dispose of waste solids, liquids, and gases.

2. EC/LSS Interface Requirements
   a. Containment and storage of feces.
   b. Removal of odor.
   c. Urine sample containment, storage, and overboard dump.

6.3 COMMUNICATIONS/DATA/INSTRUMENTATION SYSTEM

The **recommendation** for the Communications/Data/Instrumentation System shown in Figure 6.7 was based on three major factors. These are: (1) no TV requirement, (2) minimum modifications to the CM, and (3) low cost. Table 6.3 outlines the equipment types recommended for this approach.

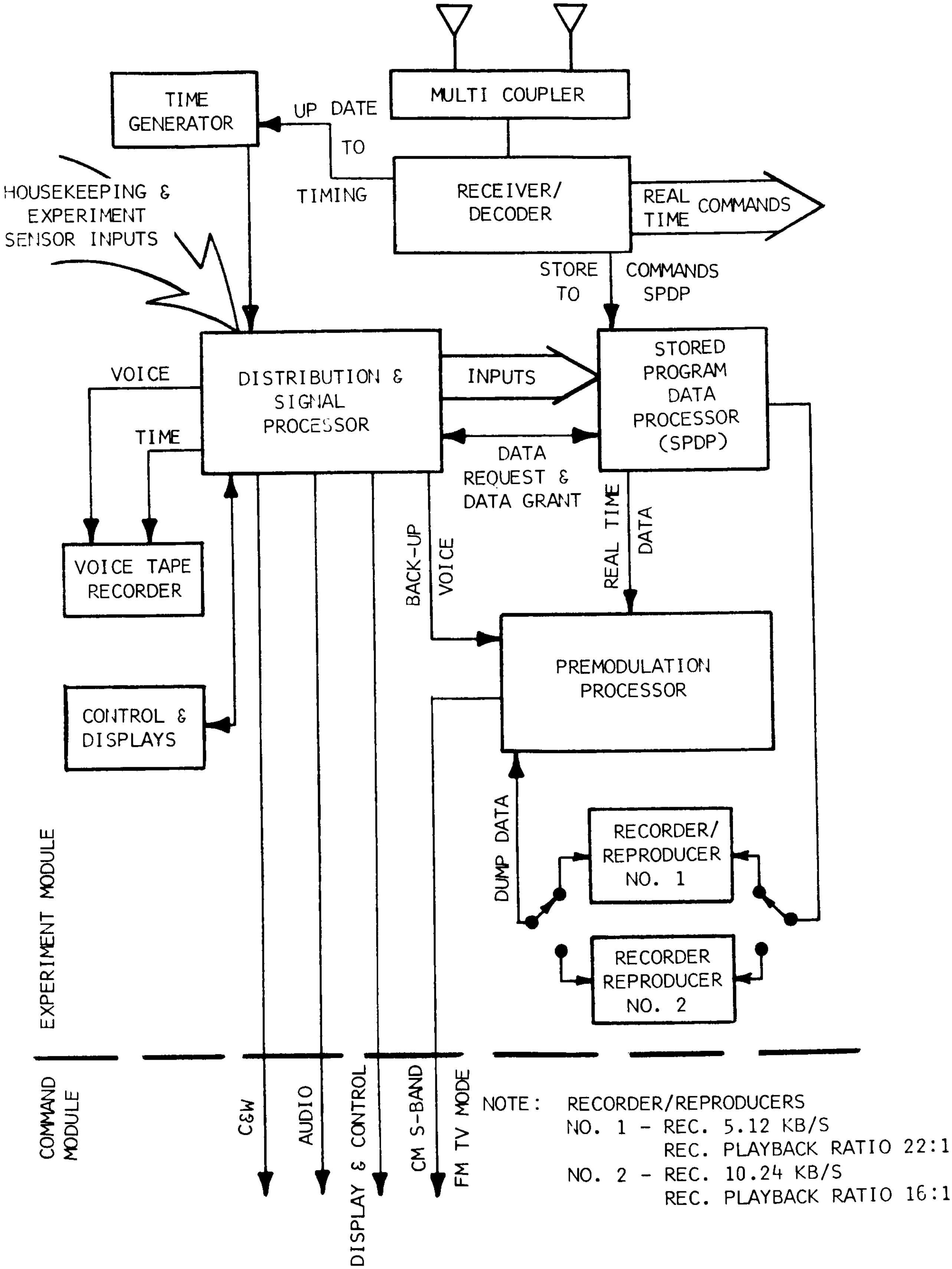
The communications system is based on utilizing the CM S-band frequency modulated (FM) mode for transmission of the Experiment Module (EM) operational and experimental data. This transmission spectrum is depicted in Figure 6.8. The CM S-band phase modulation(PM) mode will be used for the transmission of CM data.

The following assumptions have been employed in a preliminary assessment of the antenna system:

a. Gain requirement -- -13 db
b. Vehicle rotation axis perpendicular to the sun-earth vector
c. The EM configuration would be such that the effects of shading, multipath, etc., will be similar to those produced by the LM on the Apollo CM antennas.

6.3.1 Antenna System

An analysis of the communication requirements for the S-band communications from the CSM indicates that adequate coverage can be obtained using portions of the present Block II antenna system. The most suitable configuration would employ the CSM S-band flush mounted antennas located as shown on Figure 6.11. It was found, from Block II measurements, that each antenna provides hemispherical coverage at the -13 db level. The antenna patterns shown on Figure 6.9 are Radiation Distribution Plots (RDP's) of the S-band Omni-antennas on the CSM/LM ascent stage configuration. These RDP's show the recorded signal levels over a complete sphere in two degree increments. Each number on these RDP's represents a signal strength in db below the maximum gain of the antenna system. The shaded area on the RDP represents the area in which S-band communications will not be possible based on circuit margin data.



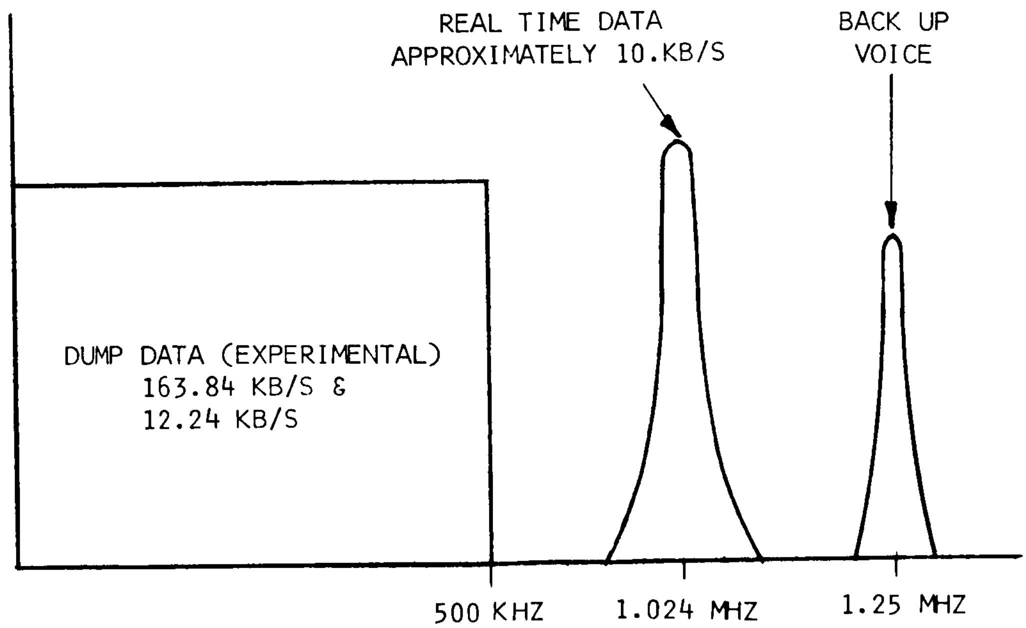
COMMUNICATIONS/DATA SYSTEM

FIGURE 6.7

RECOMMENDED EQUIPMENT

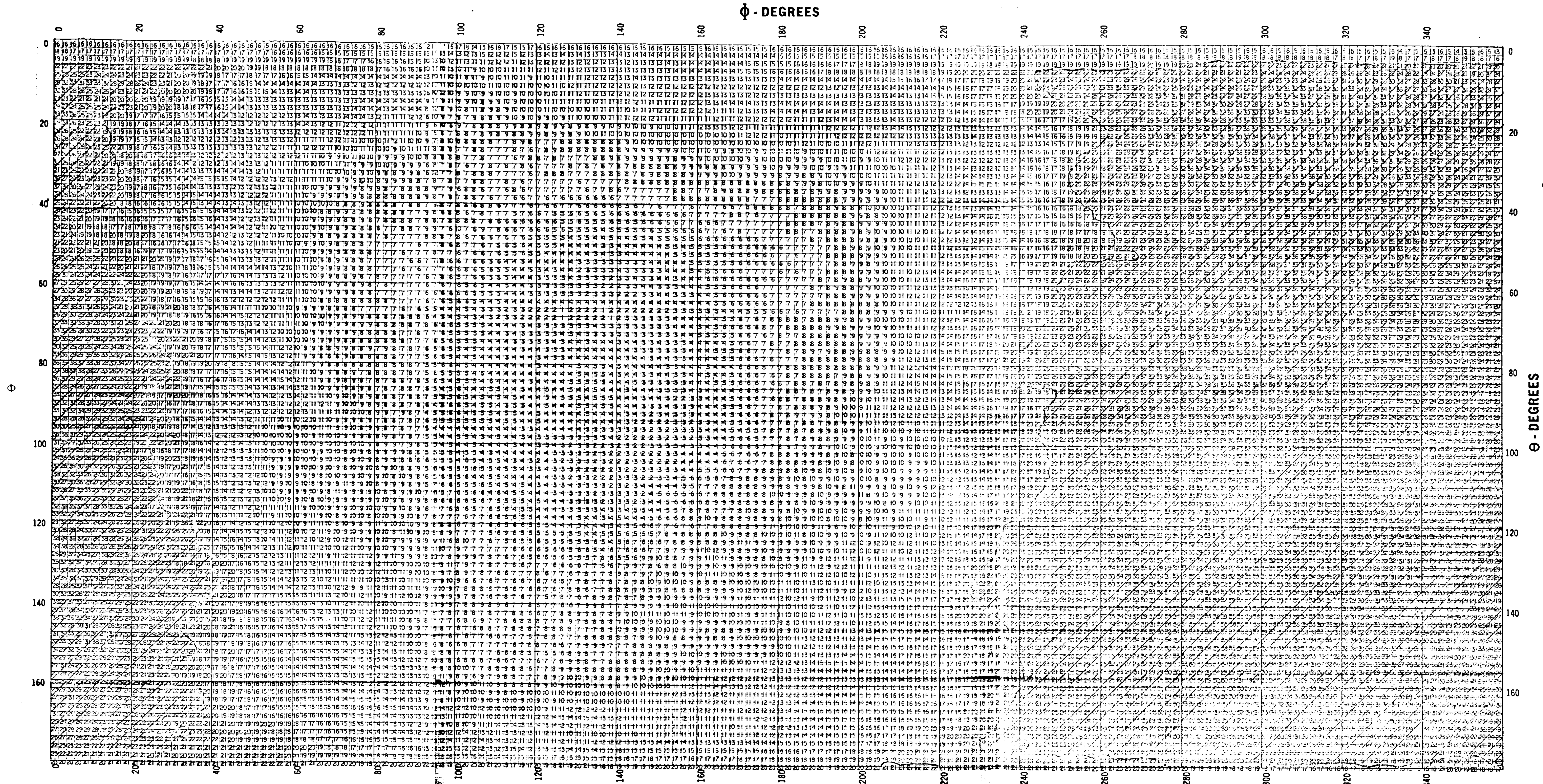
EQUIPMENT LISTING	TYPE	WEIGHT (LBS)	POWER (WATTS)
STORED PROGRAM DATA PROCESSOR	AAP DEVELOPMENT	35	18
RECORDER/REPRODUCER #1	MODIFIED ATM (AAP)	15	15
RECORDER/REPRODUCER #2	MODIFIED ATM (AAP)	15	15
PREMODULATION PROCESSOR	APOLLO CM	11	12
TIME GENERATOR	APOLLO CM	10	18
DISPLAY AND CONTROL	NEW	?	?
SIGNAL CONDITIONER	APOLLO LM (MOD)	55	35
VOICE TAPE RECORDER	AAP DEVELOPMENT	9	13
COMMAND RECEIVER/DECODER	LMDCA	15	12
ANTENNAS	APOLLO	8	?
POWER AMPLIFIER	APOLLO LM	2	80
TRANSPONDER	APOLLO LM	20	?

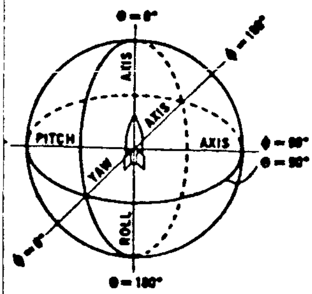
TABLE 6.3



TRANSMISSION SPECTRUM

FIGURE 6.8


φ - DEGREES
θ - DEGREES
θ
φ = 270°
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340



TEST PROGRAM OR VEHICLE	:	BLOCK II CSM/LM ASCENT
INSTRUMENTATION SYSTEM	:	MSC ANTENNA
PROJECT	:	APOLLO
DATE	:	7/15/1967
PATTERN NUMBER	:	94-C
ORGANIZATION	:	IESD-ESB-ANTENNA SYSTEMS SECTION
ENGINEERS	:	J. LINDSEY
ANTENNA TYPE	:	OMNI A LOCATED AT $\phi = 135°$
FREQUENCY RANGE	:	S-BAND
PATTERN MEASUREMENT FREQUENCY	:	2287.5 MHZ
PREDOMENANT POLARIZATION	:	RHC
MODEL SCALE	:	FULL
LOCATION OF POINT P'Y ($\phi = 0$, $\theta = 90°$)	:	-Z AXIS
GAIN PLOT	:	☒
POLARIZATION RECORDED	:	LINEAR ☐ $E\phi$, ☐ $E\theta$, CIRCULAR, ☒ RH, ☐ LH
PHASE-ANGLE PLOT	:	☐
PHASE-AGL ANGLE RECORDED	:	☐ δ, ☐ δ'

PHASE ANGLES ORE RECORDED VALUES IN DEGREES MULTIPLIED BY 10

GAINS ARE IN DECIBELS BELOW A REFERENCE LEVEL OF ± 8.4 DB RELATIVE TO AN ISOTROPIC ANTENNA OF RHC POLARIZATION

▨ -13 DB OR LOWER

RADIATION DISTRIBUTION PLOT FIGURE 6.9

The RDP is laid out so that the top of the sheet represents the nose of the experiment module and the bottom represents the tail or engine housing as indicated on Figure 6.10.

The CSM S-band antenna system, if capable of being manually switched, would provide complete communications capability. Switching from one pair of antennas to the other would only be required when changing from ground stations that are on opposite sides of the spacecraft trajectory longitude. This switching could easily be programmed such that the correct antenna could be selected by the astronaut in advance of a particular ground station on any particular orbit. The only vehicle orientation constraint is that the relation of antenna pairs A and B to the spin axis is as shown on Figure 6.11, which indicates the existing antenna coverage and the spin axis location. If the spacecraft is not roll stabilized then the switching rate would be increased by the frequency of the roll, causing an undesirable work load on the astronaut.

Some investigation has been done in the area of Level Comparison Switching of the Spacecraft S-band Antennas similar to that used on the early Apollo flights for the C-band system. It is recommended that consideration be given to the employment of this automatic technique to eliminate the operational constraints.

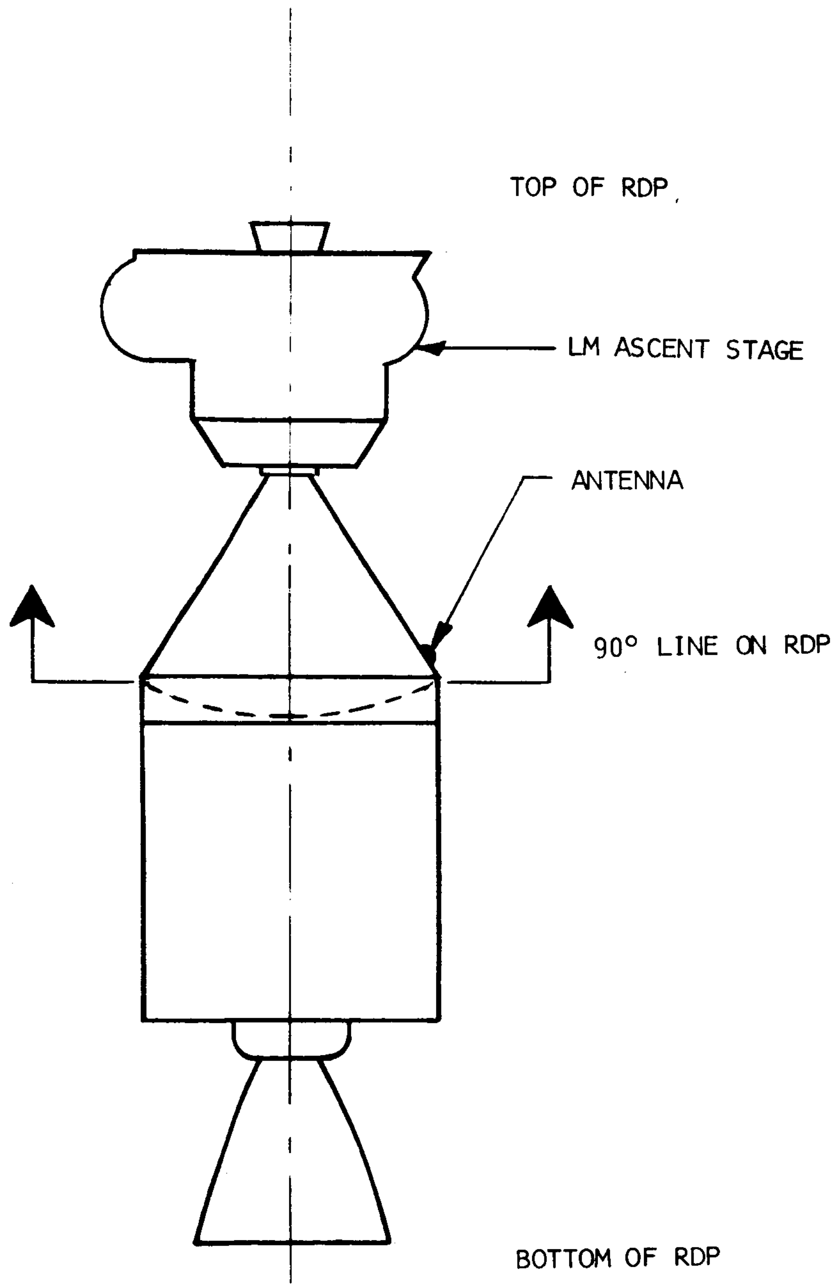
6.3.2 Pre-Modulation Processor

The Pre-modulation Processor (PMP), required in the system, functions as a processor and mixer to frequency multiplex the various data channels prior to application ot the S-band transmitter. It accomplished the function of placing high bit rate dump data on base band, real time low bit rate data on a subcarrier of 1.024 MH_z. In addition, the PMP received the updata link signal, demodulates this signal, and converts it to the digital form for input to the control equipment. In the case where the CM FM transmitter is used only as backup as far as CM usage goes. To accomplish EM data pre-modulation function, the present CM PMP design is acceptable.

6.3.3 Data System

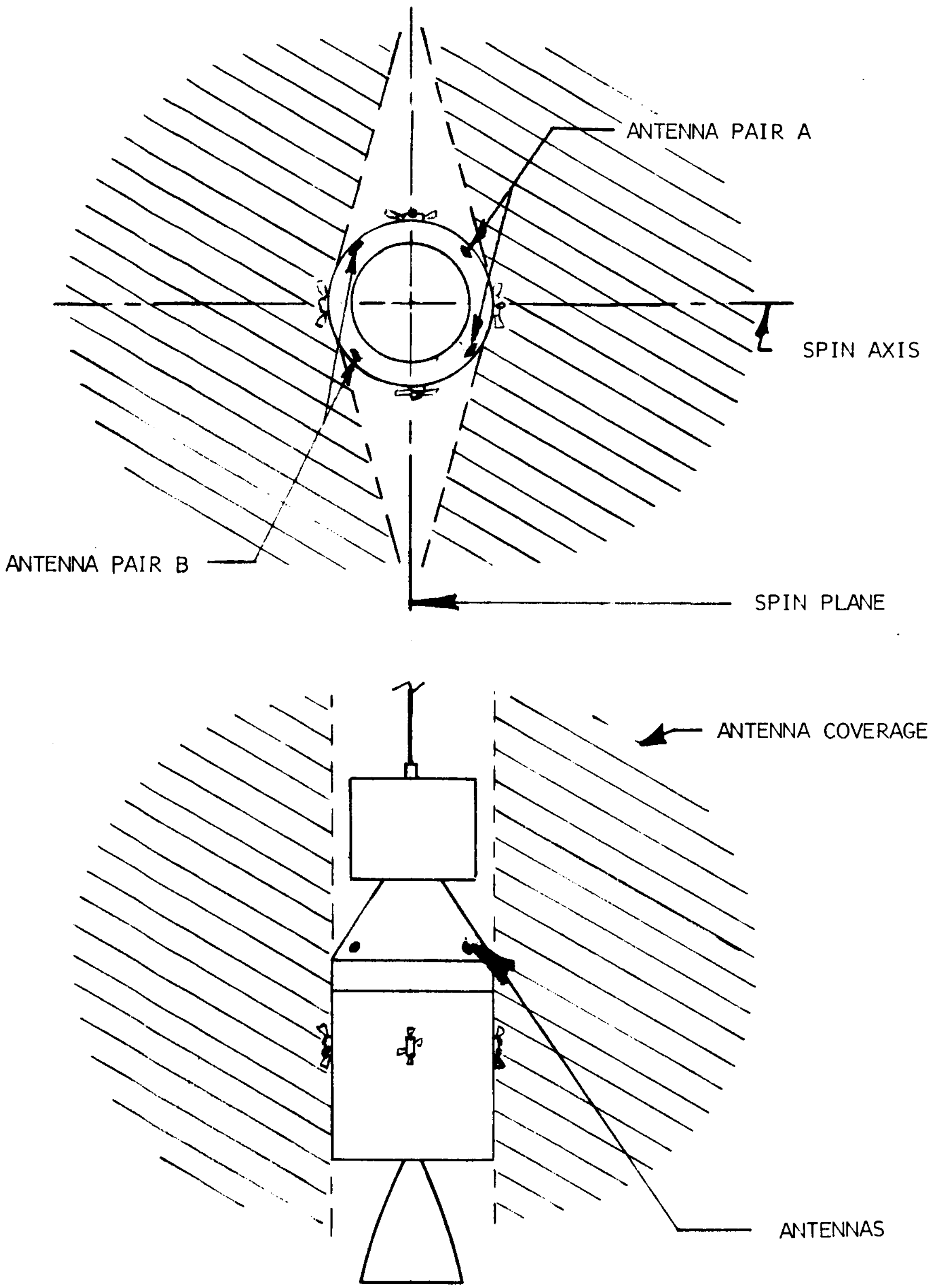
The data system is the Stored Program Data Processor (SPDP) being developed for the AAP program. It accepts analog, bi-level, and serial digital data from the data sources (operational and experimental) and processes these data into a time-multiplex output for transmission to Earth, for onboard storage, for Ground Support Equipment (SGE) processing, and for other external control equipment(e.g., onboard display).

The SPDP utilizes a programmable memory to store several PCM sampling formats, and remotely located data multiplexer/encoders to minimize spacecraft wiring requirements. The system will



RDP ORIENTATION

FIGURE 6.10



CSM S-BAND ANTENNA COVERAGE

FIGURE 6.11

accommodate up to 16 of the 64-channel multiplexers to provide a maximum system capacity of 1024 bi-level digitized channels. Instrumentation requirements of the EM can be satisfied with eight of these multiplexers. System channel sampling rates, sample formats, and output PCM bit rates are programmable, allowing optimum sampling formats and bit rates to be selected for realtime data transmission and/or data recording. Selection of the system's programmable functions, and the programming of the system memory, can be accomplished in flight via the up-data link command system. Up to four PCM sampling formats and bit rates can be selected by the crew through discrete "push-button" commands. The SPDP also provides an interface with the displays and controls panel which allows a crew member to select and observe on his display the value of any housekeeping or experiment data parameter.

6.3.4 Instrumentation Timing System

The instrumentation timing system will provide a common time reference for correlation of all spacecraft data, both that stored on board the spacecraft and that telemetered..

There is a requirement to be able to update the spacecraft timer from the ground by means of the updata link. This feature eliminates the need for the data reduction facility to make time base corrections to the spacecraft data in order that it can be properly correlated.

The Apollo CSM's central timing equipment(CTE) will be used without modifications since it meets all of this mission's requirements.

An alternate timer (CGT-200A), developed and qualified for use in the Apollo SC 012's Medical Data Acquisition System, is available for use on this mission if the time up-data requirement does not exist. The advantages of the CGT-200A timer are its reduced weight, power, physical size, and cost.

6.3.5 Signal Conditioning

The signal conditioning system will be used for amplifying, shaping, mixing, or, in general, processing the raw transducer signals in a manner which makes them compatible with other instrumentation equipment. The conditioned signals are utilized in one or more of the following ways. They may be recorded, telemetered, displayed to the crew, or fed into the caution and warning systems.

A modified LM signal conditioning electronic assembly (SCEA) would be used. However, if weight, power, and volume become prime mission considerations, the microminiature programmed power signal conditioning system (MPPSCS) now under Apollo supporting development could be provided in time to support this mission. The MPPSCS could reduce the system's weight, power, and volume by 75%.

.3.6 Data Storage Equipment

The artificial "g" experiment data storage equipment will collect and handle two basic types of data. These data types are: (1) housekeeping and experiment digital data and (2) voice analog data.

.3.6.1 General

1. Digital Data Storage Equipment
   The digital data storage equipment consists of two magnetic tape recorder/reproducers -- one to record a 5120 bits per second(bps) data rate and to reproduce it at 112,640 bps (Unit #1) and one to record a 10,240 bps (Unit #2). The total reproduce time for each device is approximately seven minutes. A recorder, selected by command, receives and records either RZ or NRZ (L), or NRZ (S) at record/reproduce ratios of 22:1 and 16:1 respectively. The synchronizing clock will be reconstructed during data reproduction and will be available at the tape recorder output. The digital data storage equipment may be controlled by the SPDP or from a remote control center. Refer to Tables 6.4 and 6.5 for configuration details.

3.6.2 Itemized Components

1. Digital Data Storage Equipment
   Tables 6.4 and 6.5 contain the basic parameters of five magnetic tape systems. Each of the three recorders of Table 6.4 are applicable to Unit #1 and each of the two recorders of Table 6.5 are applicable to Unit #2. Unit #1 configurations A and B and Unit #2 configuration A are manufactured by the Borg-Warner Corporation. Unit #1 configuration C and Unit #2 configuration B are manufactured by RCA. Each unit is considered to be off-the-shelf hardware, however, each unit will require minor modification to tailor the device to the artificial "g" experiment application.

   It is recommended that configuration B, Table 6.4, which is a modified ATM recorder, be utilized as Unit #1 and that configuration A, Table 6.5, which is a modified ATM recorder, be utilized as Unit #2.

2. Voice Data Storage Equipment
   Table 6.6 contains the basic parameters of the voice cartridge loaded magnetic tape recorder. The basic unit is being developed as a portable cartridge-loaded instrumentation tape recorder/reproducer under Apollo Supporting Development

UNIT NO. 1 CONFIGURATIONS

	A	B	C
RECORD TAPE SPEED (IPS)	3.2	2.56	1 7/8
REPRODUCE TAPE SPEED (IPS)	70.4	56.3	41 1/4
SPEED RATIO (RECORD:REPRODUCE)	22:1	22:1	22:1
DATA FORMAT INPUT	RZ OR NRZ(L)	RZ OR NRZ(L)	RZ OR NRZ(L)
DATA RATE INPUT (BPS)	5.12×10^3	5.12×10^3	5.12×10^3
DATA FORMAT OUTPUT	BI-Ø(L), NRZ(L) OR NRZ(S)	BI-Ø(L), NRZ(L) OR NRZ(S)	BI-Ø(L), NRZ(L) OR NRZ(S)
DATA RATE OUTPUT (BPS)	112.64×10^3	112.64×10^3	112.64×10^3
RECORD TIME (MIN)	154	117	154
REPRODUCE TIME (MIN)	7.0	5.3	7.0
DATA CAPACITY (TOTAL BITS)	47.3×10^6	36×10^6	47.3×10^6
BIT PACKING DENSITY (BPLI)	1600	2000	2730
ERROR RATE	1 IN 10^5	1 IN 10^5	1 IN 10^5
POWER CONSUMPTION (WATTS)	15 @ 28 V DC	15 @ 28 V DC	15 @ 28 V DC
TAPE LENGTH (FEET)	1232	1500	1444
WEIGHT (POUNDS)	15	15	15
SIZE (INCHES^3)	8 X 8 X 5	8 X 8 X 5	
TAPE OPERATION	BI-DIRECTIONAL 2 TAPE PASSES	BI-DIRECTIONAL 1 TAPE PASS	BI-DIRECTIONAL 1 TAPE PASS
ENCLOSURE	HERMETICALLY SEALED	HERMETICALLY SEALED	HERMETICALLY SEALED

TABLE 6.4

UNIT NO. 2 CONFIGURATIONS

	A	B
RECORD TAPE SPEED (IPS)	5.12	3 3/4
REPRODUCE TAPE SPEED (IPS)	82	60
SPEED RATIO (RECORD:REPRODUCE)	16:1	16:1
DATA FORMAT INPUT	RZ OR NRZ(L)	RZ OR NRZ(L)
DATA RATE INPUT (BPS)	10.24×10^3	10.26×10^3
DATA FORMAT OUTPUT	BI-Ø(L), NRZ(L) OR NRZ(S)	BI-Ø(L), NRZ(L) OR NRZ(S)
DATA RATE OUTPUT (BPS)	163.84×10^3	162.84×10^3
RECORD TIME (MIN)	112	112
REPRODUCE TIME (MIN)	7	7
DATA CAPACITY (TOTAL BITS)	68.8×10^6	68.8×10^6
BIT PACKING DENSITY (BPLI)	2000	2730
ERROR RATE	1 IN 10^5	1 IN 10^5
POWER CONSUMPTION (WATTS)	15 @ 28 V DC	15 @ 28 V DC
TAPE LENGTH (FEET)	1434	2100
WEIGHT (POUNDS)	15	15
SIZE (INCHES^3)	8 X 8 X 5	
TAPE OPERATION	BI-DIRECTIONAL 2 TAPE PASES	BI-DIRECTIONAL 1 TAPE PASS
ENCLOSURE	HERMETICALLY SEALED	HERMETICALLY SEALED

TABLE 6.5

RECORD TAPE SPEED (IPS)	1 7/8
FREQUENCY RESPONSE (HZ)	
DIRECT RECORD	200 - 2800
FM	DC - 624
SIGNAL-TO-NOISE (DB-RMS/RMS)	
DIRECT RECORD	26
FM	30
RECORD TIME PER TAPE CARTRIDGE (HOURS)	3.75
TAPE LENGTH (FEET)	702
WEIGHT (POUNDS)	
TAPE CARTRIDGE	1.5
TAPE RECORDER	7.5
SIZE (INCHES^3)	
TAPE CARTRIDGE	0.75 X 4.375 X 9.25
TAPE RECORDER	3 1/2 X 5 1/2 X 11
TAPE OPERATION	BI-DIRECTIONAL 3 TAPE PASSES
POWER CONSUMPTION	13 WATTS @ 28 V DC

VOICE TAPE RECORDER CONFIGURATIONS

TABLE 6.6

Program, and is configured as a voice recorder for the artificial "g" experiment application.

6.3.7 Television

A requirement for television was not specified for the mission. However, if TV is required then it is recommended that a system, as depicted by the attached block diagram, Figure 6.12, be utilized. This system can provide commercial quality TV for on-board safety monitoring and as an operational aid. The performance characteristics are specified on Table 6.7. Lesser quality TV (but somewhat better than Apollo TV) can be provided on a dump basis to the ground station.

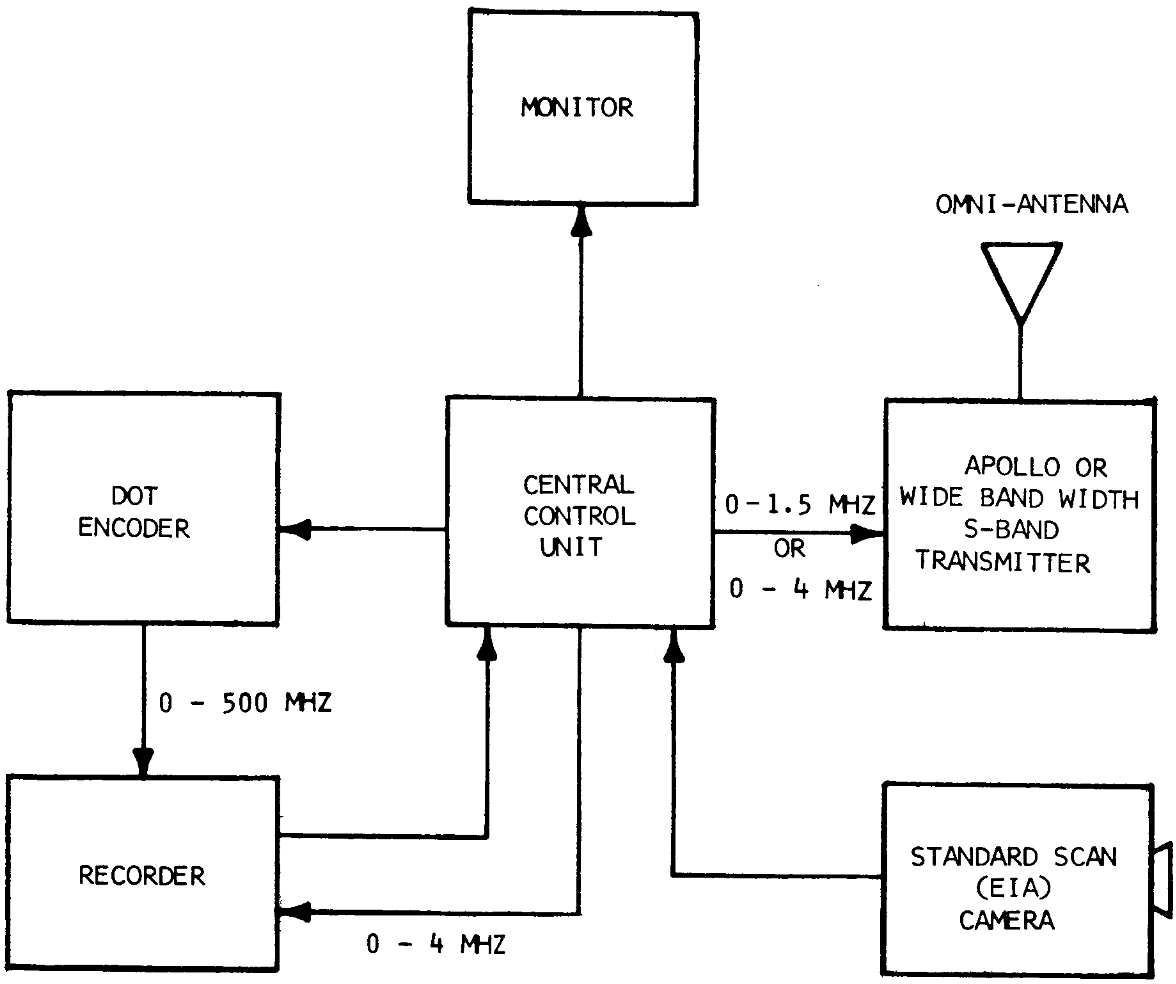
One, or more, standard scan TV cameras could be employed to obtain full coverage of the mission. Referring to Figure 6.12 the central control unit is required to switch cameras, or select signal routing for real time transmission, or for delayed playback. In the latter case, the standard scan TV signal is bandwidth compressed by a dot encoder such that up to eight times as much television activity can be recorded as can be transmitted in real time.

The quality of the television signal is directly proportional to the communication link. It is recommended that the link have an information bandwidth of at least 4 MHz(Note: This requires the addition of a wide band transmitter that has been flown on the Saturn Program.) and that this link be utilized for TV while the CM FM link is used for the remainder of EM data. If existing Apollo equipment is selected for the transmitter, the band width limitation of 1.5 MHz will reduce the picture quality to a still usable level. In this case, the CM or EM transmitter could be used for television or data.

6.4 SUMMARY

The subsystems have been studied to determine the design characteristics, weight, and power requirements and are summarized on Table 6.8. The Electrical Power System, Environmental Control System, Communications/Data System and Instrumentation systems were presented in this section. The data on crew systems and expendables were developed from the information presented in Section 4 and Section 9.

The Stabilization and Control System data are presented in Section 8 and the experiments data were developed from Section 5.



TELEVISION SYSTEM

FIGURE 6.12

TV PERFORMANCE CHARACTERISTICS

SYSTEM ELEMENTS	SIZE (INCHES) W	H	L	WEIGHT (LBS.)	POWER AT 28 VDC (WATTS)	BANDWIDTH (MHZ)	SCAN MODE
STANDARD (EIA) CAMERA	1.5	3.0	4.5	3.0	10.0	3.0	EIA
CM MONITOR	7.0	10.0	12.0	20.0	24.0	4.0	EIA
MSFC MONITOR UNDER DEVELOPMENT FOR ATM	9.5	L2.5	L2.0	29.7	45.0	8.0	EIA
CM VIDEO RECORDER	14.0	6.1	10.0	25.0	62.0	0.5	NA
DOT INTERLACE OPTION	6.0	2.0	4.0	1.0	3.0	0.5	5 FRAMES/SEC 60 FIELDS/SEC

TABLE 6.7

SUBSYSTEM SUMMARY

ITEM	WEIGHT LB	ELECTRICAL POWER, W AVG	MAX	MIN	QUANTITY & TYPE
EPS	(719)	(100)	(250)	(95)	
PEAKING BATTERIES	57	-	-	-	2 CM
BATTERY CHARGER	4				1 CM
INVERTERS	114	70	175	70	2 ATM/CMG
CONTROL EQUIPMENT	44	30	75	25	CM
WIRING & INSTALLATION	500				
EC/LSS	(480)	(178)	(178)	(178)	
ATMOSPHERIC PURIFICATION & SUIT LOOP	60	14	14	14	CM
THERMAL CONTROL	237	124	124	124	CSM
ATMOSPHERIC CONDITIONING	35	31	31	31	
SUIT LOOP OXYGEN SUPPLY	110	-	-	-	1 LM DESCENT
WATER MANAGEMENT	22	-	-	-	CM
WASTE MANAGEMENT	7	7	7	7	
INSTRUMENTATION	9	2	2	2	CM
CREW SYSTEMS	(97)	-	-	-	
SEATS & RESTRAINTS	50	-	-	-	
BUNKS	20	-	-	-	2
CONSTANT WEAR GARMENTS	6	-	-	-	8
FOOD STORAGE & PREPARATION	11	-	-	-	-
PERSONAL EQUIPMENT	10	-	-	-	-
COMMUNICATIONS/DATA	(142)	(51)	(170)	(6)	
STORED PROGRAM DATA PROCESSOR (SPDP)	49	10	20	0	1
PMP	10	10	30	0	1 CM
S-BAND FM TRANSPONDER	38	7	34	0	1
POWER AMPLIFIER	32	18	90	0	1
TIMER	10	6	6	6	1
ANTENNA	3	-	-	-	2

TABLE 6.8

SUBSYSTEM SUMMARY (cont'd)

ITEM	WEIGHT LB	ELECTRICAL POWER, W AVG	MAX	MIN	QUANTITY & TYPE
INSTRUMENTATION	(87)	(84)	(94)	(54)	
SIGNAL CONDITIONER	17	-	-	-	1
TAPE RECORDER	13	-	-	-	1
DC-DC CONVERTER	7	44	44	44	1
CONTROLS & DISPLAYS	50	-	-	-	
ILLUMINATION	20	40	50	10	
SENSORS (HOUSEKEEPING)	15	-	-	-	
STABILIZATION & CONTROL	(610)	(305)	(790)	(0)	
BMAG'S	22	100	200	0	4 CM
ACCELEROMETERS	20	26	99	0	3
AUXILIARY SCS	8	21	46	0	
CMG COMPUTER & SERVO ELECT.	150	109	320	0	ATM
CMG	410	49	125	0	1 ATM
EXPERIMENTS	(517)	(32)	(705)	(0)	
EXPERIMENT APPARATUS	491				
STORAGE	26				
EXPENDABLES	(189)	-	-	-	
FOOD & HYGIENE	52				
FILM & MAGNETIC TAPE	37				
ECS FILL & CONSUMABLES	100				
TOTALS	2841	750	2187	343	

7.0 EXTENSION AND DEPLOYMENT

Since two of the concepts considered in the Artificial Gravity Study required deployment to obtain the desired length, a rather thorough investigation into the deployment device was necessary. Several concepts were studied; the results are presented in this section.

7.1 DEPLOYMENT MECHANISMS

The extension mechanism used in developing the space station's artificial gravity must occupy a minimum storage volume, yet be able to extend to the required spin radius. Also, it must be strong enough to maintain the proper relationship between the two rotating masses. Three general types of extension mechanisms were investigated: the flexible structure for the Moby Dick, a rigid metal tube concept similar to the Ryan or DeHavilland type of extending boom, and various cable arrangements.

7.1.1 Flexible Structure

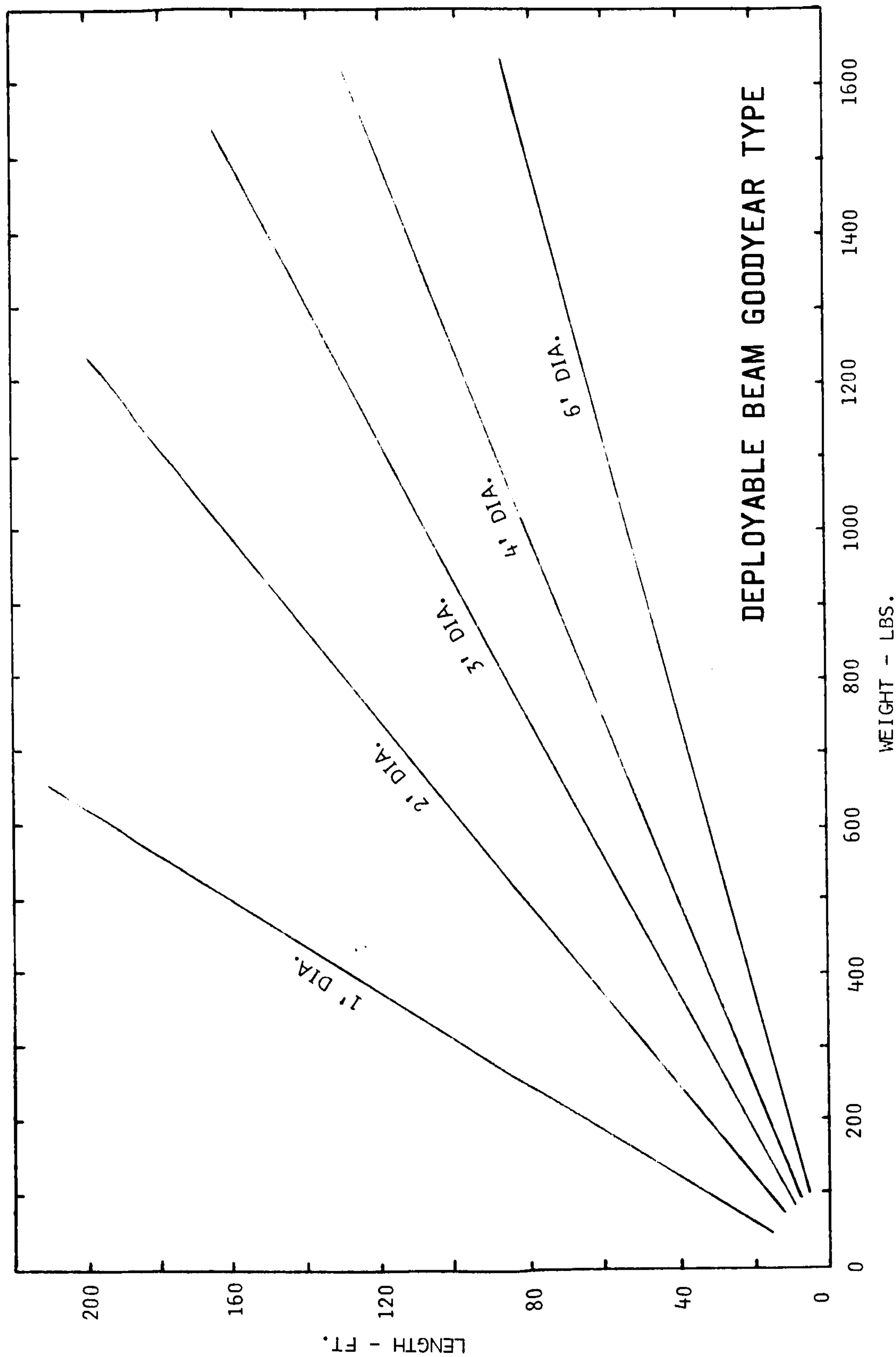
The Moby Dick uses a Goodyear type of tube or beam. This is a good example of a flexible beam which gains its operational rigidity through the application of internal pressure. The beam stows in a fairly compact package; however, its extended length is restricted because of the available stowage volume.

The flexible structure is comparatively heavy - Figure 7.1 gives the weight-to-length relationships of various diameter beams - and requires some type of device to control its extension rate. This could be a cable arrangement, synchronized with the pressurization unit. This beam is subject to possible pressure leakage, which would destroy the rigidity of the tube, thereby eliminating its advantage over a flexible connection.

7.1.2 Ryan/DeHavilland Type Structure

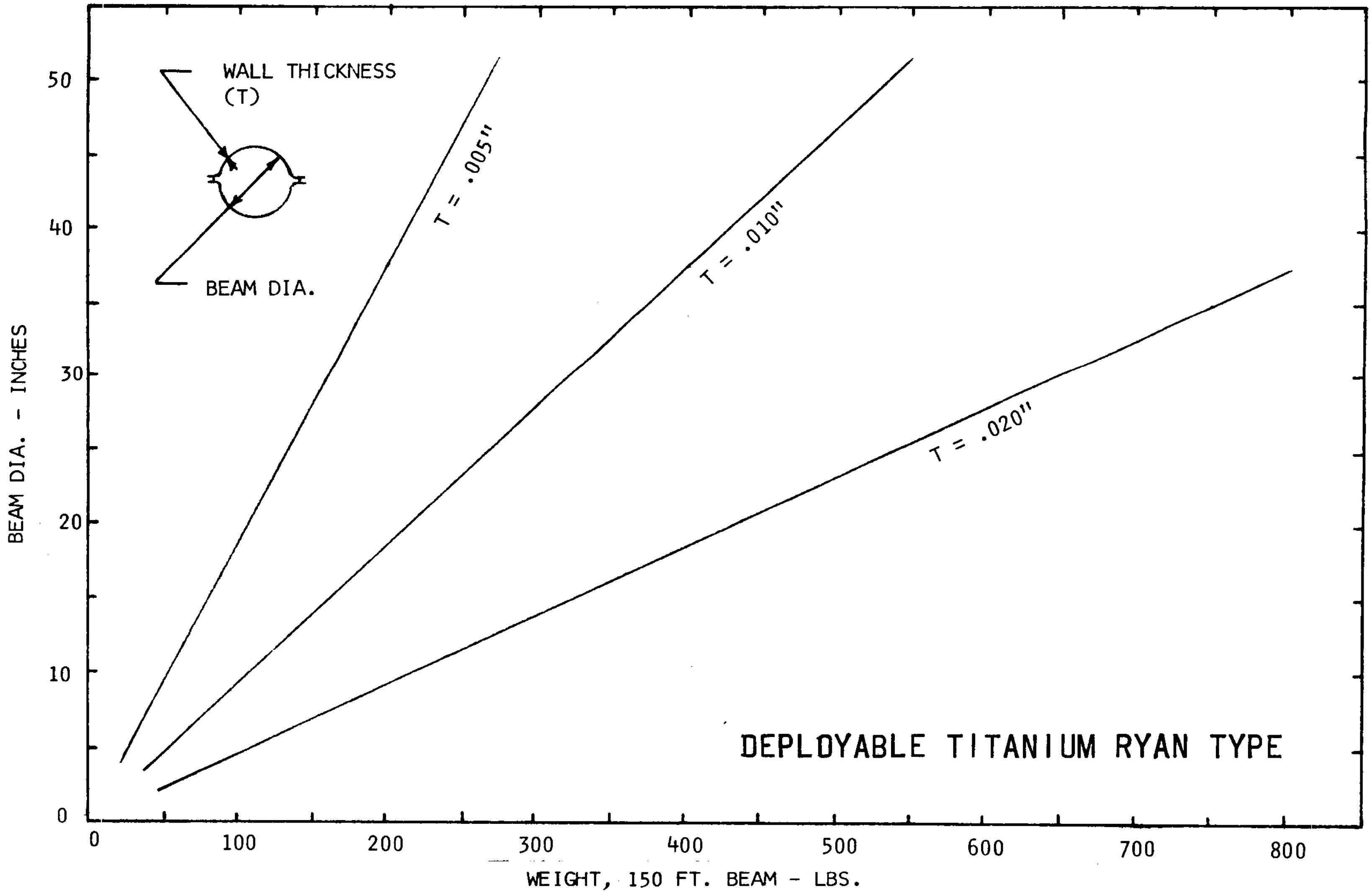
In an effort to eliminate the extension control mechanism required for the flexible structure beam, a Ryan/DeHavilland type structure was investigated.

These beams have the rigid characteristics desired for spacecraft spin-up. This stiffness, along with the Ryan/DeHavilland type extension system, eliminates the necessity of additional control during the beam's deployment. Its rigidity is governed by its diameter and skin thickness; however, in this type of beam, the material thickness limits the maximum diameter which can be formed without permanent deformation when it is flattened on the storage drum. Figure 7.2 gives the weight and diameter relationship of various wall thicknesses and Figure 7.3 indicates the weight-to-length relationship for various diameter beams.



DEPLOYABLE BEAM GOODYEAR TYPE
1' DIA.
2' DIA.
3' DIA.
4' DIA.
6' DIA.
WEIGHT - LBS.
LENGTH - FT.
0
200
400
600
800
1000
1200
1400
1600
0
40
80
120
160
200

FIGURE 7.1



WALL THICKNESS
(T)
BEAM DIA.
T = .005"
T = .010"
T = .020"
DEPLOYABLE TITANIUM RYAN TYPE
BEAM DIA. - INCHES
WEIGHT, 150 FT. BEAM - LBS.
0
10
20
30
40
50
0
100
200
300
400
500
600
700
800

FIGURE 7.2

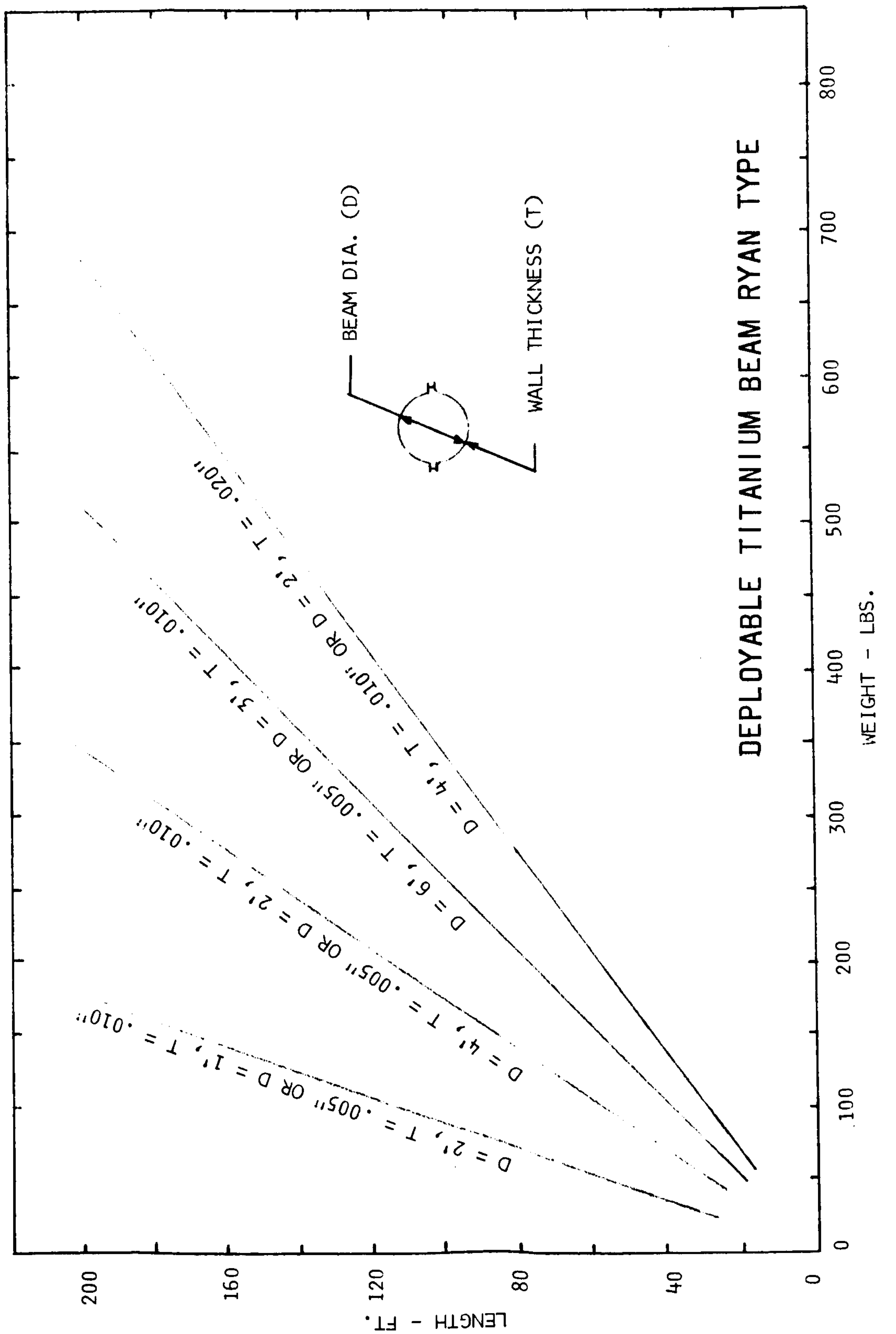

DEPLOYABLE TITANIUM BEAM RYAN TYPE
BEAM DIA. (D)
WALL THICKNESS (T)
D = 4', T = .010" OR D = 2', T = .020"
D = 6', T = .005" OR D = 3', T = .010"
D = 4', T = .005" OR D = 2', T = .010"
D = 2', T = .005" OR D = 1', T = .010"
WEIGHT - LBS.
0
100
200
300
400
500
600
700
800
LENGTH - FT.
0
40
80
120
160
200

FIGURE 7.3

The weight penalty for this type of structure appears to be quite severe.

Figure 7.4 shows a cross-section of another method of utilizing the Ryan type structure. The side walls are composed of segments which permit drum storage of a large diameter, rectangular cross-section tube. However, as is readily seen, the weight for this concept is also prohibitive.

7.1.3 Cables

The cable deployment system was investigated as another method of deploying and maintaining an artificial gravity space station. Several cable arrangements, using 6 x 19 flexible, corrosion-resistant, steel cables to provide the required radius, were examined. The weight-to-length relationships for the various cable combinations under consideration are shown on Figure 7.5. In the multiple cable system, the load was considered to be equally distributed among the cables.

7.1.4 Comparison of Deployment Mechanisms

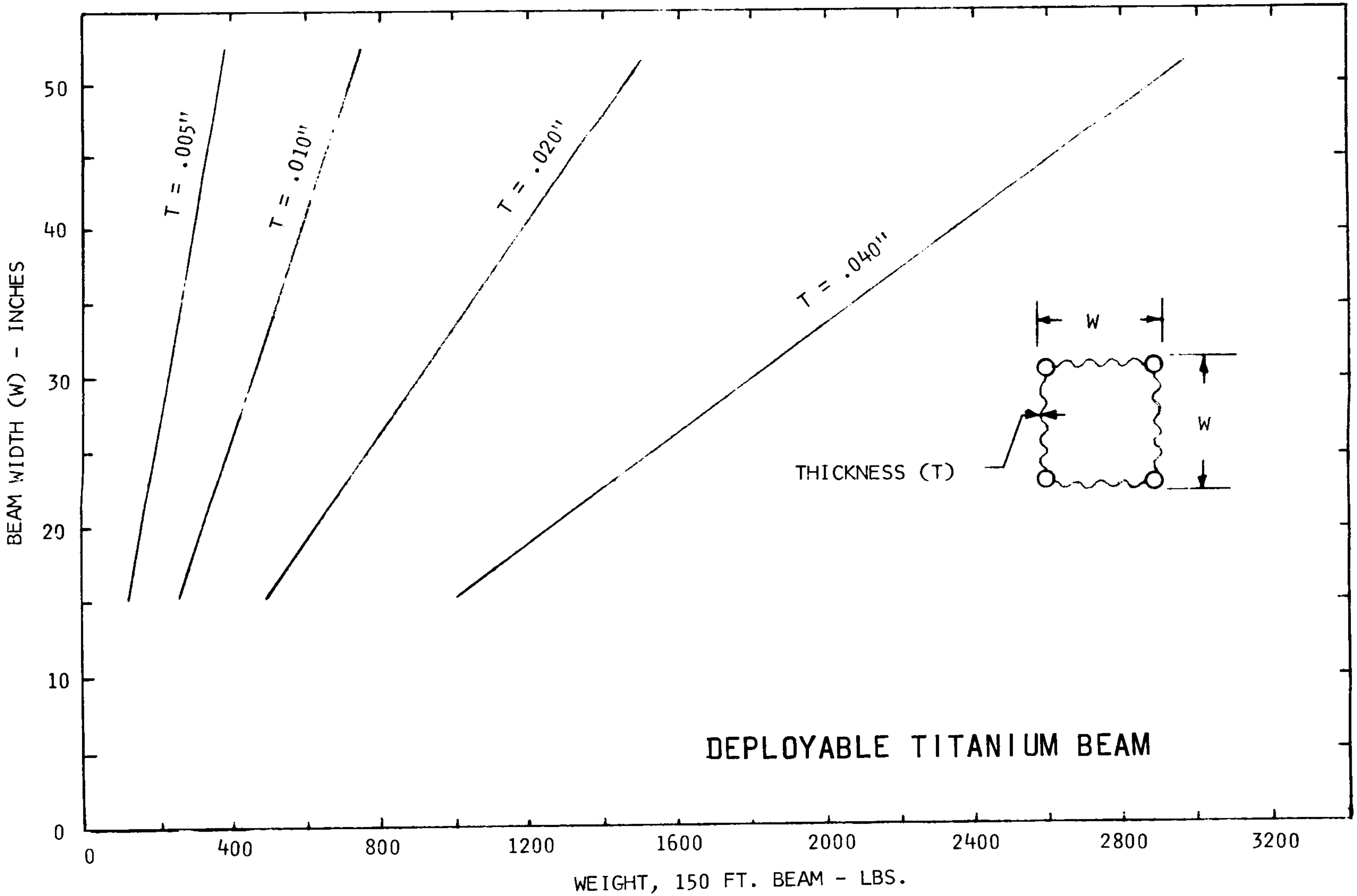
The general weight-to-length relationships of the three artificial gravity deployment systems which were considered in this study are shown in Figure 7.6. In order to obtain a more vivid relationship of the three systems, the Goodyear and Ryan type structures were restricted from one, 24-inch beam to four, four-inch beams and the number of cables is varied from one to four. Weight economy dictates the use of the cable deployment and control system, even though this flexible system has less spin-up rigidity than either the Ryan or Goodyear structure. If the problems of stabilization and control can be solved, it would appear that the single cable would be the simplest and lightest deployment mechanism.

7.2 COUNTERWEIGHT CONSIDERATIONS

Two general concepts for the counterweights of the artificial gravity station have been investigated. Figure 7.7 shows both ideas with the pertinent data.

The first idea studies utilized the spent S-IVB stage as a counterweight. For a direct injection into orbit, the maximum Experiment Module weight available is 8,100 pounds. The spin-up propellant required for this configuration is just over 300 pounds.

The alternate idea was to increase the available payload by injecting into an elliptical orbit, stage the S-IVB, circularize with the Service Module, and take the counterweight from the payload. This made an additional 2,560 pounds available in orbit. The counterweight and additional spin-up propellant must be taken from this 2,560 pounds.



DEPLOYABLE TITANIUM BEAM
T = .005"
T = .010"
T = .020"
T = .040"
W
W
THICKNESS (T)
BEAM WIDTH (W) - INCHES
WEIGHT, 150 FT. BEAM - LBS.
0
10
20
30
40
50
0
400
800
1200
1600
2000
2400
2800
3200

FIGURE 7.4

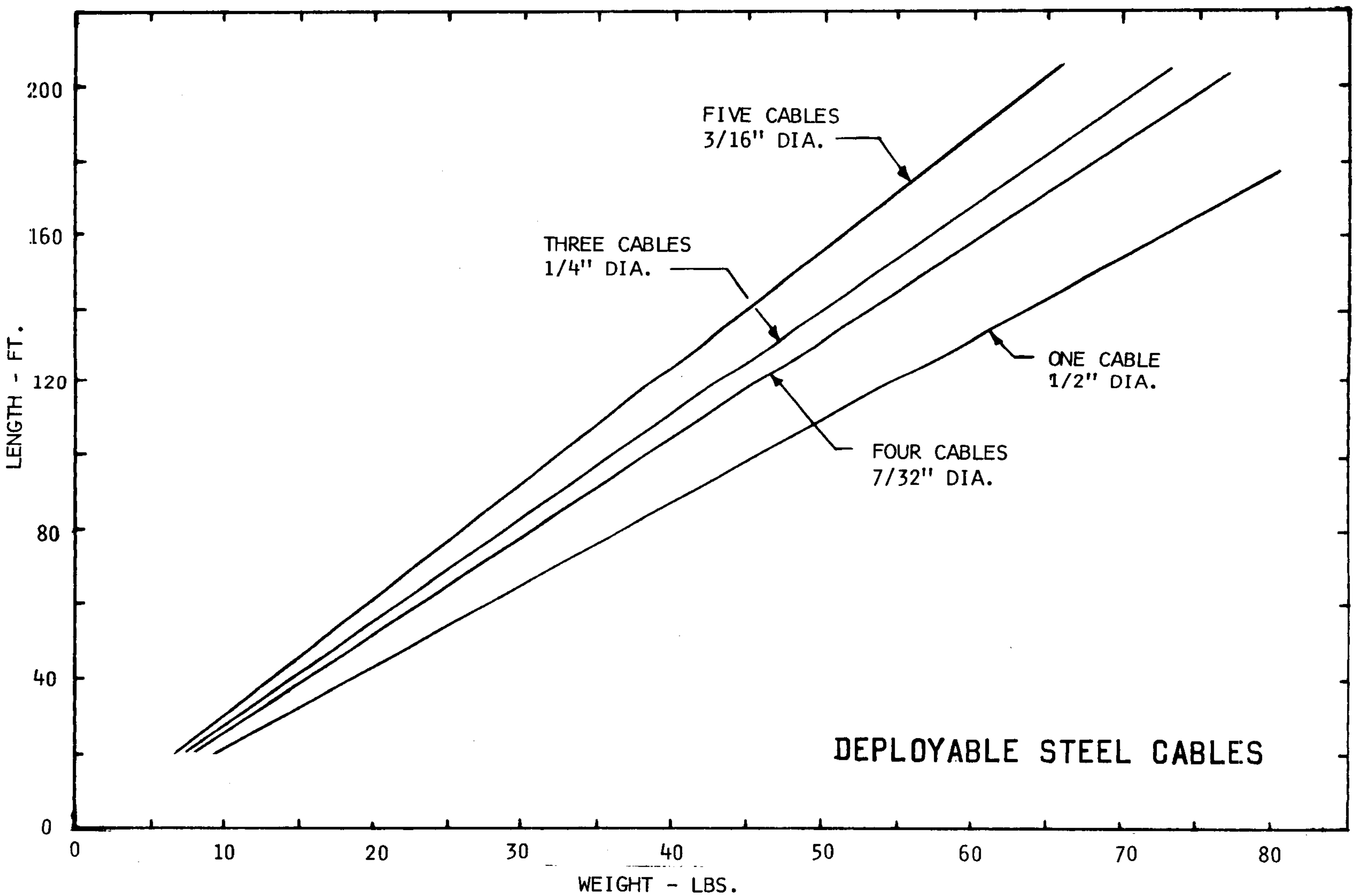
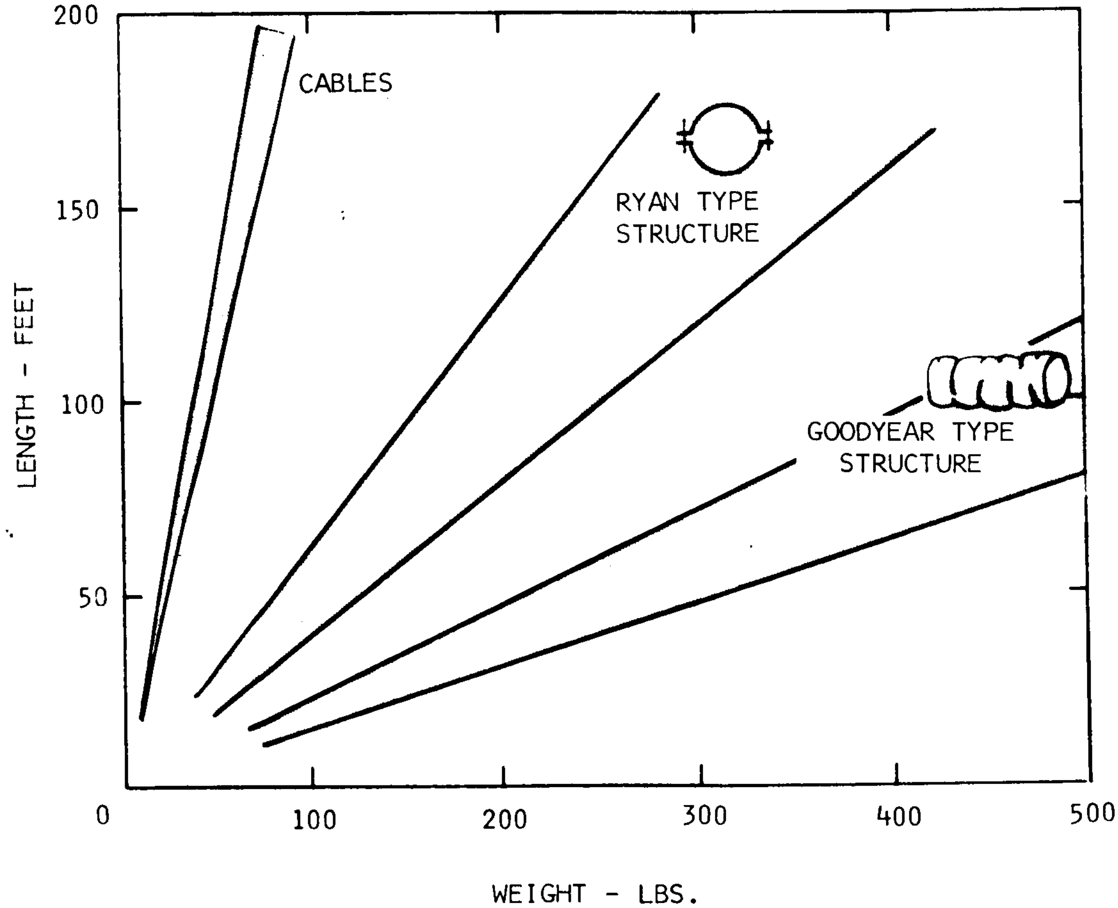

DEPLOYABLE STEEL CABLES
FIVE CABLES
3/16" DIA.
THREE CABLES
1/4" DIA.
FOUR CABLES
7/32" DIA.
ONE CABLE
1/2" DIA.
LENGTH - FT.
WEIGHT - LBS.
0
40
80
120
160
200
0
10
20
30
40
50
60
70
80

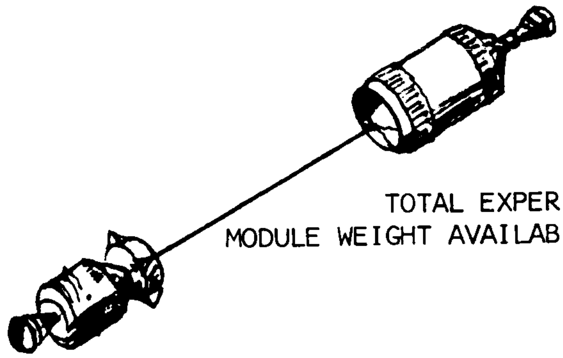
FIGURE 7.5



DEPLOYABLE BEAM STRUCTURE COMPARISON

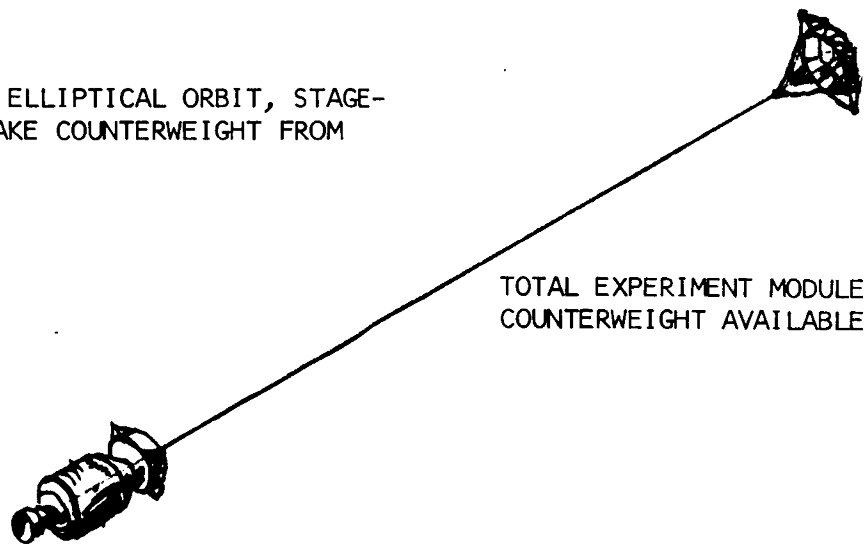
FIGURE 7.6

DIRECT S-IVB INJECTION WITH
S-IVB AS COUNTERWEIGHT



TOTAL EXPERIMENT
MODULE WEIGHT AVAILABLE = 8,100 LBS.

INJECTION TO ELLIPTICAL ORBIT, STAGE-OFF S-IVB, TAKE COUNTERWEIGHT FROM PAYLOAD.



TOTAL EXPERIMENT MODULE &
COUNTERWEIGHT AVAILABLE = 10,660 LBS.

TOTAL BALLAST WEIGHT AVAILABLE =	10,660
	8,100
	2,560

COUNTERWEIGHT CONSIDERATIONS

FIGURE 7.7

Figure 7.8 shows the amount of propellant required to spin-up the station as a function of the cable length. Obviously, the station cable length is limited by the propellant available to rotate the station. Two quads of the Service Module have sufficient propellant to rotate a configuration with approximately 500 feet of cable. If all the propellant from all four quads is used, a station with 1,000 feet of cable can be rotated, but this would be an absolute maximum. The maximum amount available for spin-up is approximately 450 pounds.

Figure 7.9 shows the results of the investigation. Weight is plotted against cable length and, as might be expected, a sufficiently long cable eliminates completely the need for a counterweight.

The lowers curve on the graph is the counterweight or ballast. For a "short cable" (1,000 ft.) approximately 3,000 pounds of ballast is required. The middle curve is the cable weight added to the ballast. To balance the CSM and Experiment Module for less than the available 2,560 pounds, approximately 1,500 feet of cable and 1,800 pounds of ballast is required.

When the top curve, the propellant required for spin-up, is added to the others, the study is completed. The lightest possible combination of ballast, cable and propellant is approximately 4,300 pounds which is 1,740 pounds heavier than the 2,560 pounds available for the system. Further, this requires 1,900 pounds of spin-up propellant which is approximately 1,500 pounds more than is available.

Thus, the only possible concept for this particular mission is that of using ths S-IVB as a counterweight and launching it direct to the circular orbit.

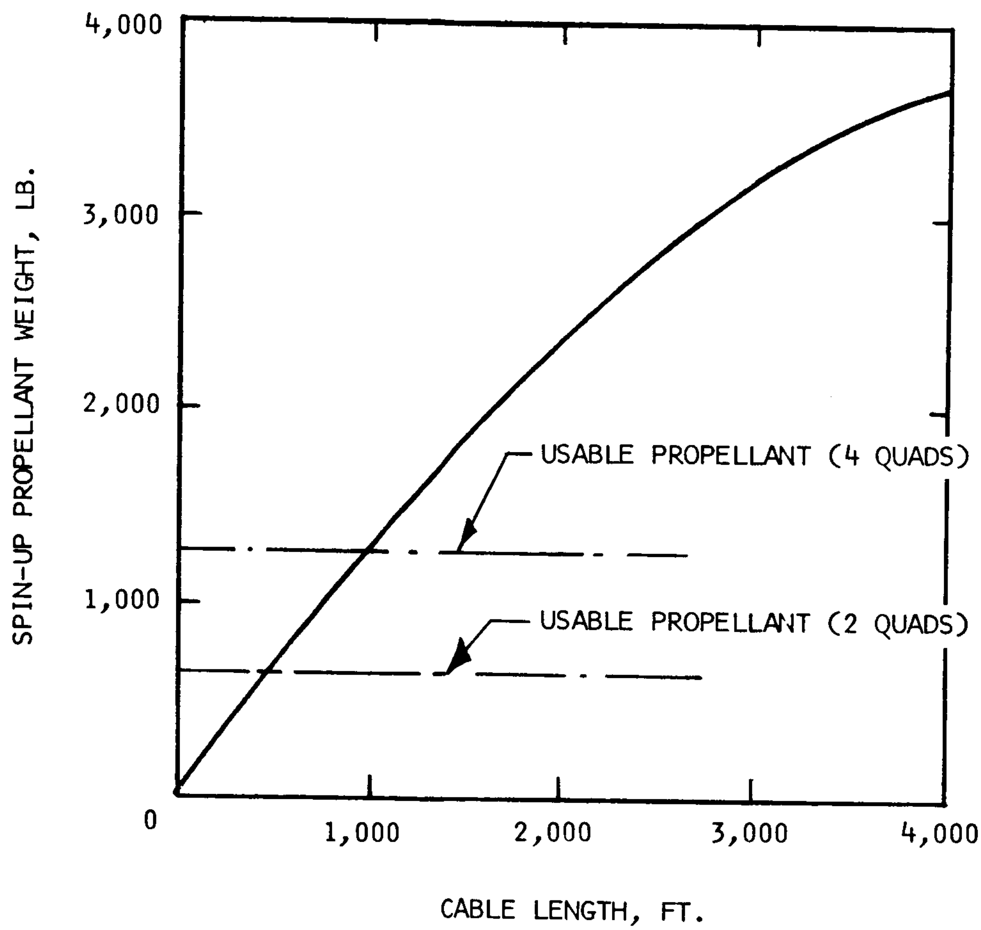
7.3 CABLE-CONNECTED CONFIGURATIONS

By evaluating the deployment mechanism studies, it is readily determined that some type of cable arrangement must be developed as a station extension device. Further, the S-IVB must be used as a counterweight.

Accordingly, the study narrows to an investigation of cable deployment mechanisms and the associated stabilization and control problems.

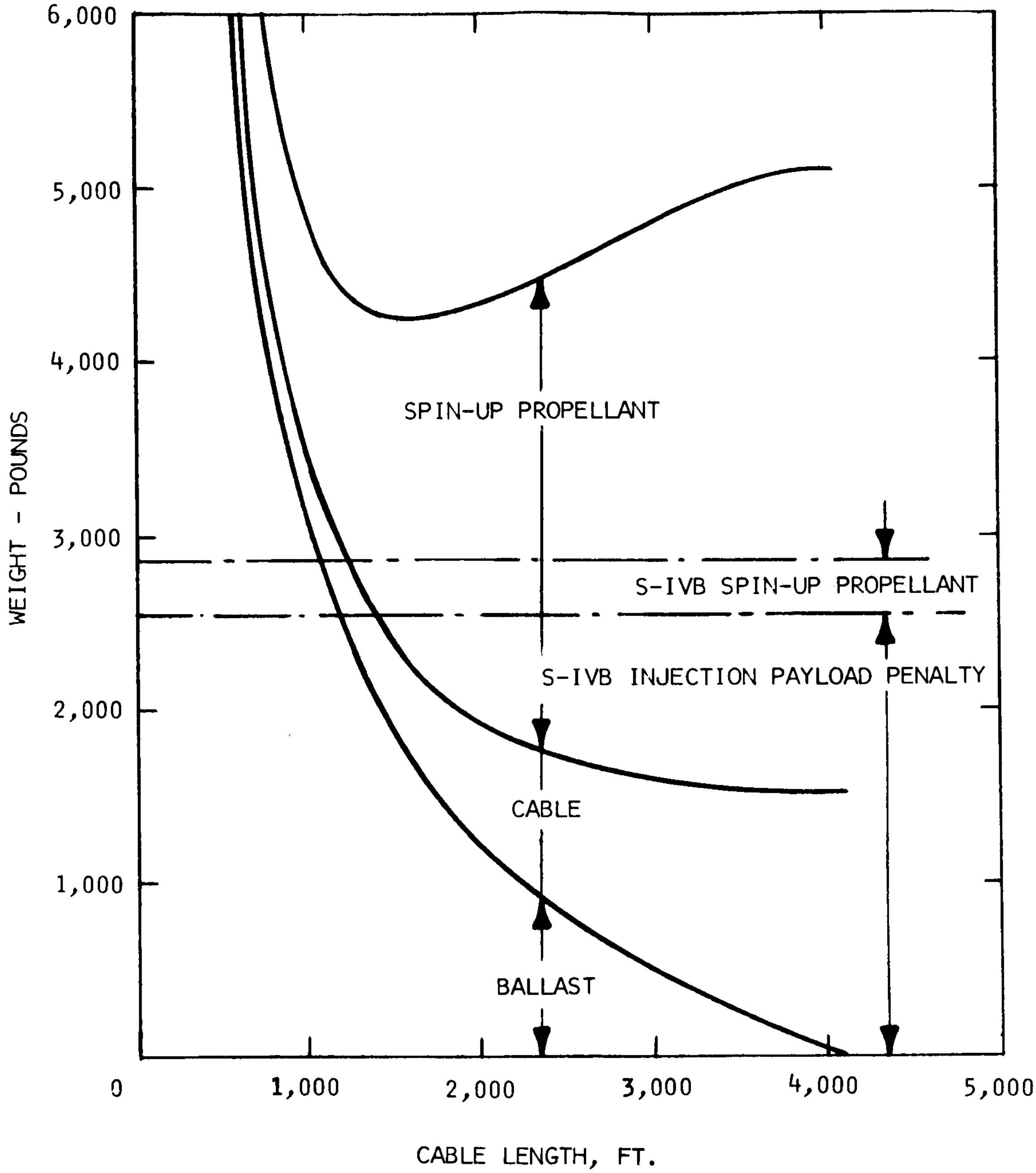
Figure 7.10 indicates the five configurations initially investigated. The Guidance and Control Division studied these concepts and indicated that the multiple cable arrangements provide better stability during the cable extension and spin-up period, but a single cable would be adequate for subsequent operations.

Accordingly, the combination configuration shown on Figure 7.11 was devised.



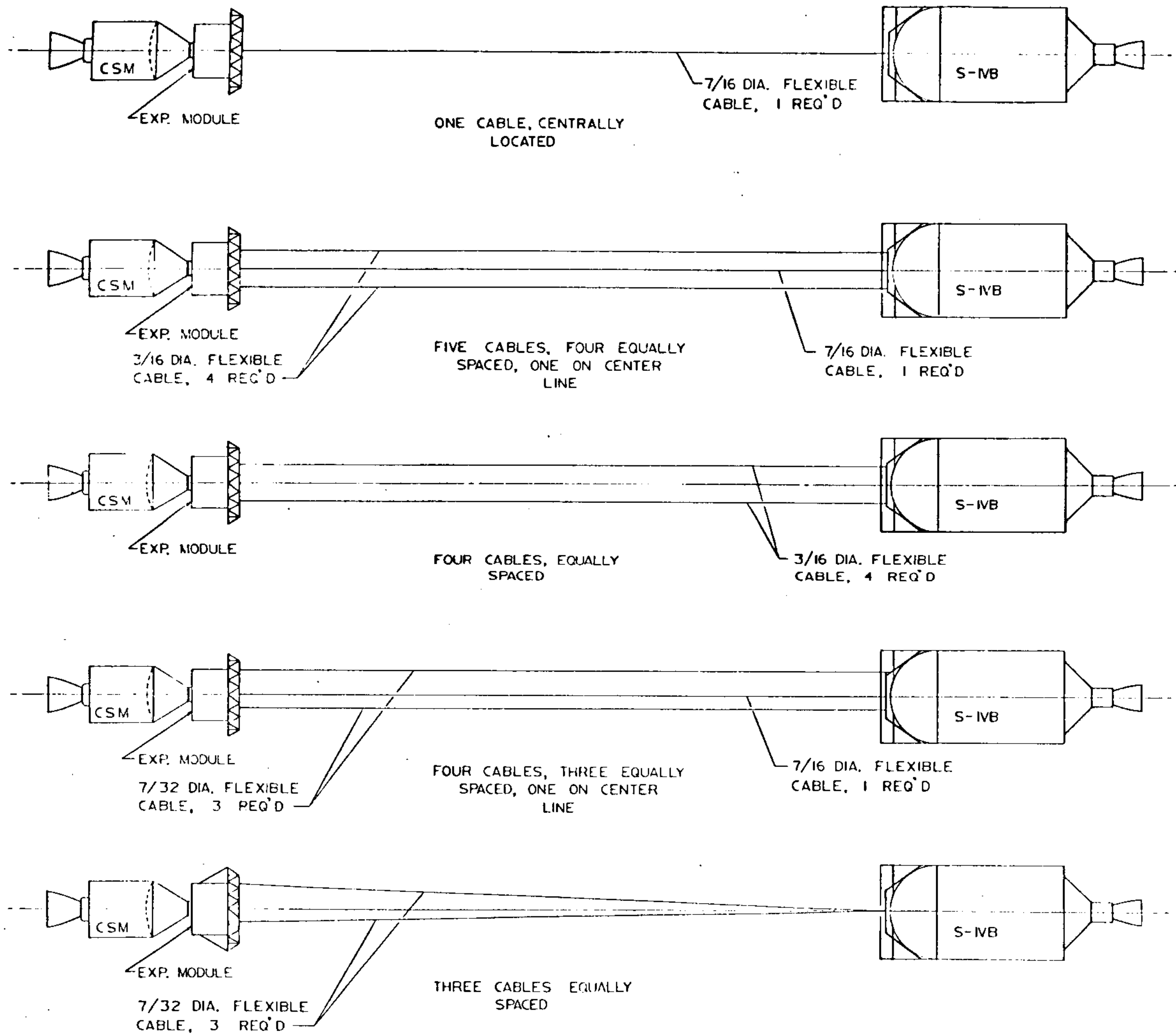
SPIN-UP PROPELLANT VS CABLE LENGTH

FIGURE 7.8



S-IVB/BALLAST TRADE-OFF

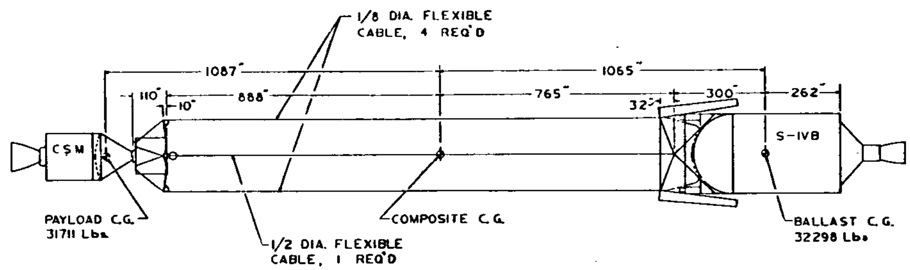
FIGURE 7.9



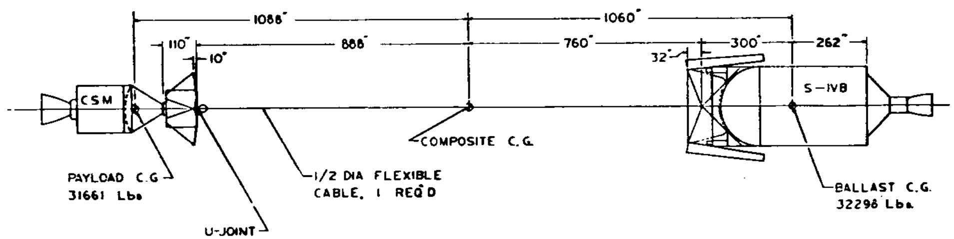
NATIONAL AERONAUTICS & SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER — HOUSTON, TEXAS

ARTIFICIAL GRAVITY CABLE ARRANGEMENT

FIGURE 7.10



FIVE CABLES – FOUR EQUALLY SPACED, ONE ON CENTER LINE



ONE CABLE CENTRALLY LOCATED

ARTIFICIAL GRAVITY
CABLE EXT. MECH.
ROTATION CONFIG.

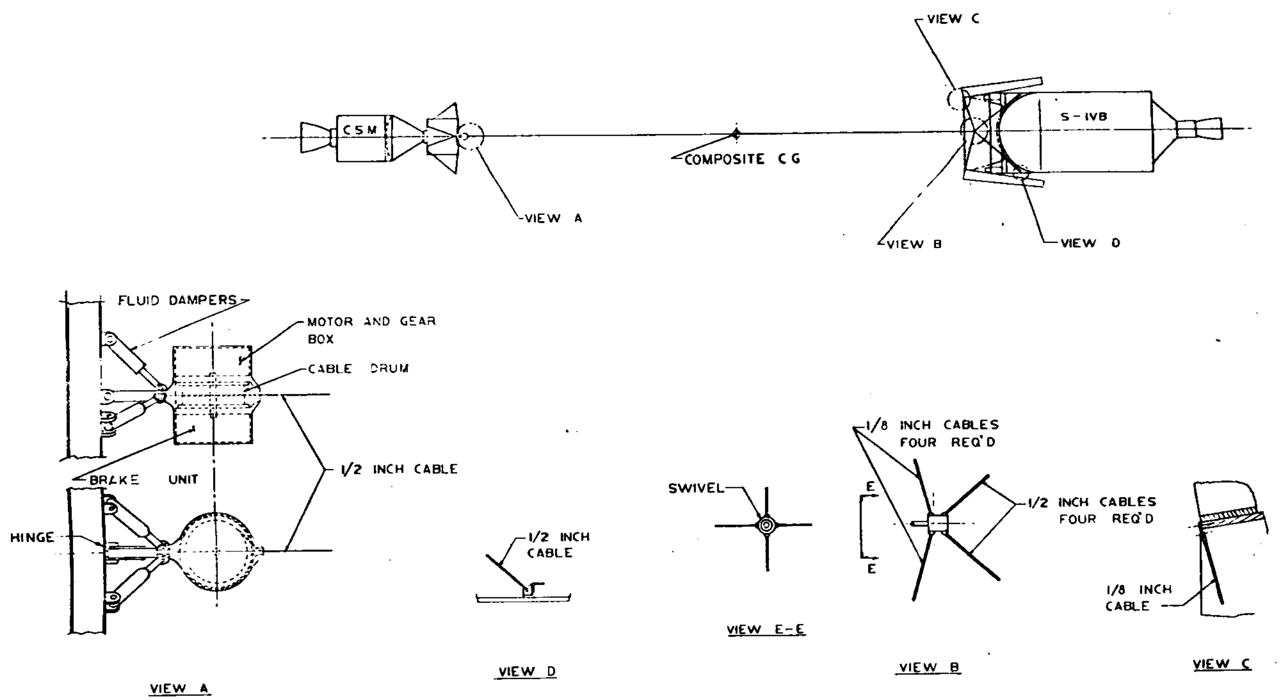
FIGURE 7.11

A five cable arrangement is used during the spacecraft spin-up and cable extension, then converted into a single cable configuration by discarding the four external cables. This was satisfactory from a control standpoint; however, the jettisoning of the extra cables was not too palatable. Further investigation indicated that a single cable deployment mechanism would be satisfactory if the cable attachment were properly designed. Figure 7.12 shows the results of these considerations.

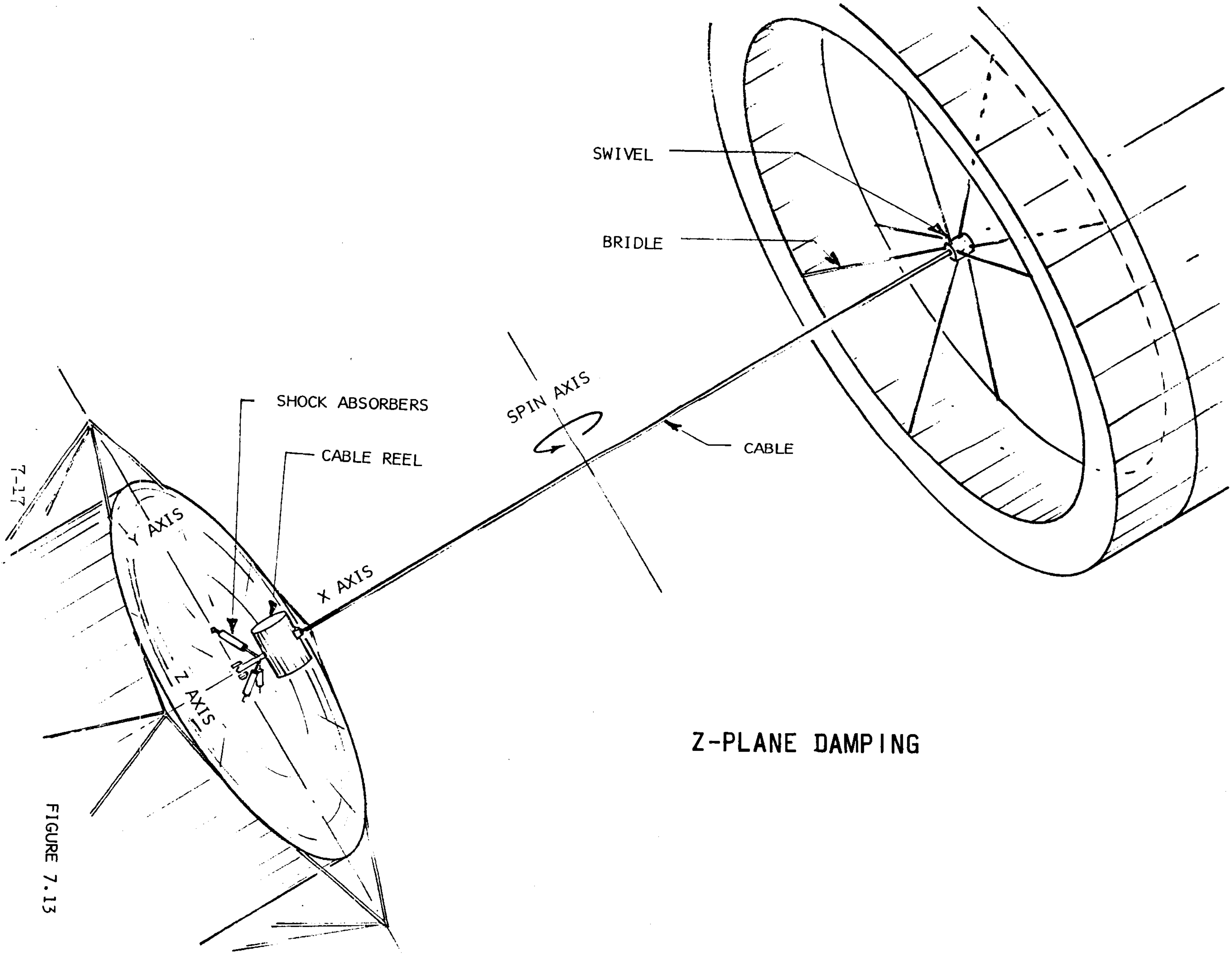
The single cable is on a braked reel that regulates the extension speed. This reel is attached to the Experiment Module through a hinge and fluid damper which provide damping of angular rates relative to the cable. Damping and stability control about the X-X axis are provided by a Control Moment Gyro mounted on the Experiment Module. Roll coupling from the S-IVB counterweight is prevented by a universal-swivel attachment in the bridle arrangement shown on Figure 7.12.

Because stabilization and control are of paramount importance to a station of this type, a thorough discussion of the problems and associated solutions is presented in Section 8.

After consideration of the various types of extendable structures and the control and stabilization problems, the single cable was selected because of its economical weight and operational simplicity. With proper cable attachment design, the single cable deployment and control system should function satisfactorily. An "artist's view" of this concept is shown on Figure 7.13.



ARTIFICIAL GRAVITY
SINGLE CABLE
PRELIMINARY INSTAL.
FIGURE 7.12



Z-PLANE DAMPING

FIGURE 7.13

8.0 GUIDANCE AND CONTROL

The guidance and control system (G&C) requirements, analysis and preliminary system definition are presented in this section. The objective of this study was to determine the control system configuration required to perform an artificial gravity experiment while making maximum use of existing Apollo G&C systems. Control studies were conducted for the Moby Dick Configurations (MD) and the Cable Connected Vehicle (CCV). Other sections have shown advantages for the CCV over the MD; therefore, any comments which are not specifically designated MD shall be with respect to the chosen configuration - the CCV.

8.1 ORIENTATION CONSTRAINTS

The orbital geometry of this mission is similar to Apollo earth orbital missions and affects new guidance and control requirements only in the spinning mode. The orbital inclination will be 28.5 degrees and the altitude approximately 130 nautical miles. The mission duration shall be up to 14 days. Thermal control of the spacecraft is best accomplished by spinning the vehicle such that all sides of the vehicle come in contact with sun rays. This is accomplished by requiring the spin vector to be normal to the sun line (Figure 8.1). This constraint will be generated by communications and can be specified as a function of launch time. The spin vector orientation will be achieved by orienting the spacecraft prior to the spin-up maneuver.

The experiment portion of the mission is to be up to 10 days duration; therefore, it is necessary to account for a 10 degree sun movement. This may be accomplished by orienting the spin vector normal to the solar ecliptic, in which case, the attitude would be totally specified, or, if communication constraints become critical the spin vector would be oriented to the mean sun position allowing a maximum 5 degree error in the solar orientation.

The orbital precession for the mission is approximately 90 degrees(Figure 8.2); therefore, the vehicle assumes practically all orientations with respect to the local vertical and horizontal. These are the critical directions with respect to gravity gradient and aerodynamic torques.

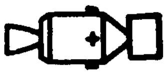
8.2 CONTROL REQUIREMENTS

This section presents the control functions and accuracy requirements that influence the control system design. A complete definition is not attempted, but those functions and requirements which are different from Apollo are defined.

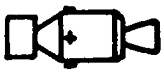
The primary function of this mission is to perform an artificial gravity experiment; that is, it is required to spin the vehicle

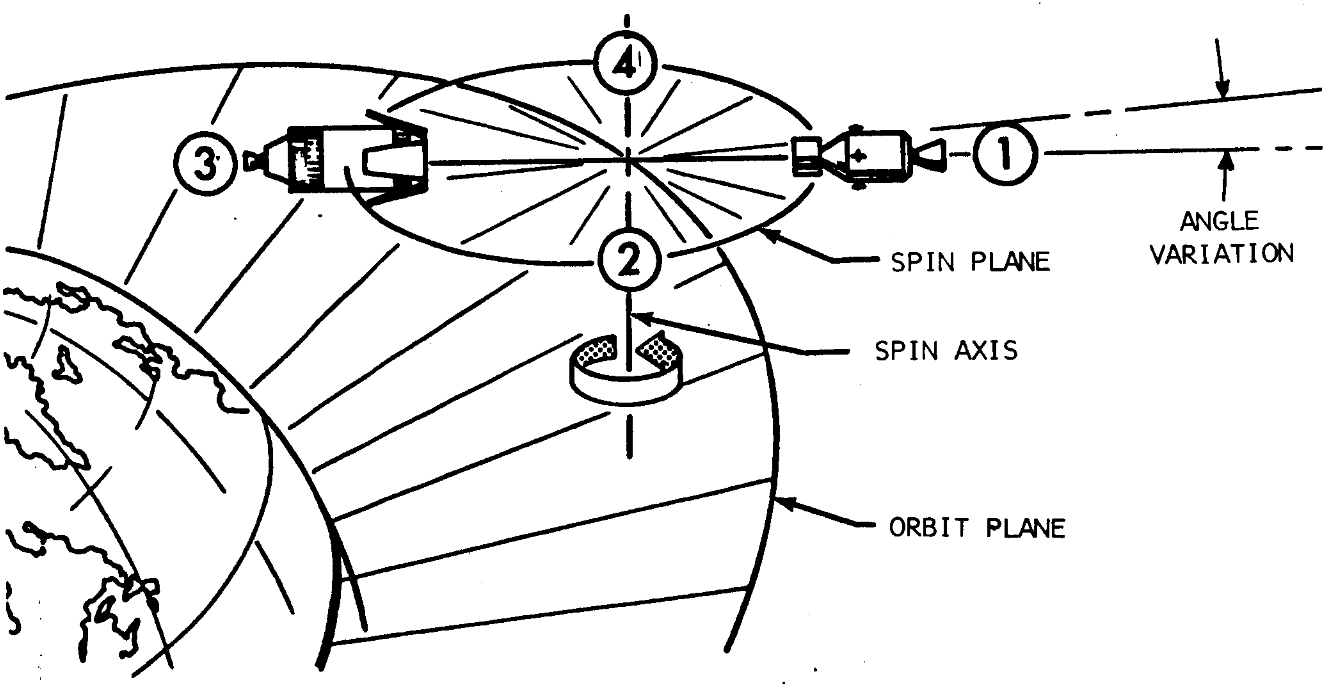
AS VIEWED
FROM SUN

1  ILLUMINATES SERVICE PROPULSION SYSTEM AND AFT OF SERVICE MODULE

2  SIDE TOWARD SUN COMPLETELY ILLUMINATED

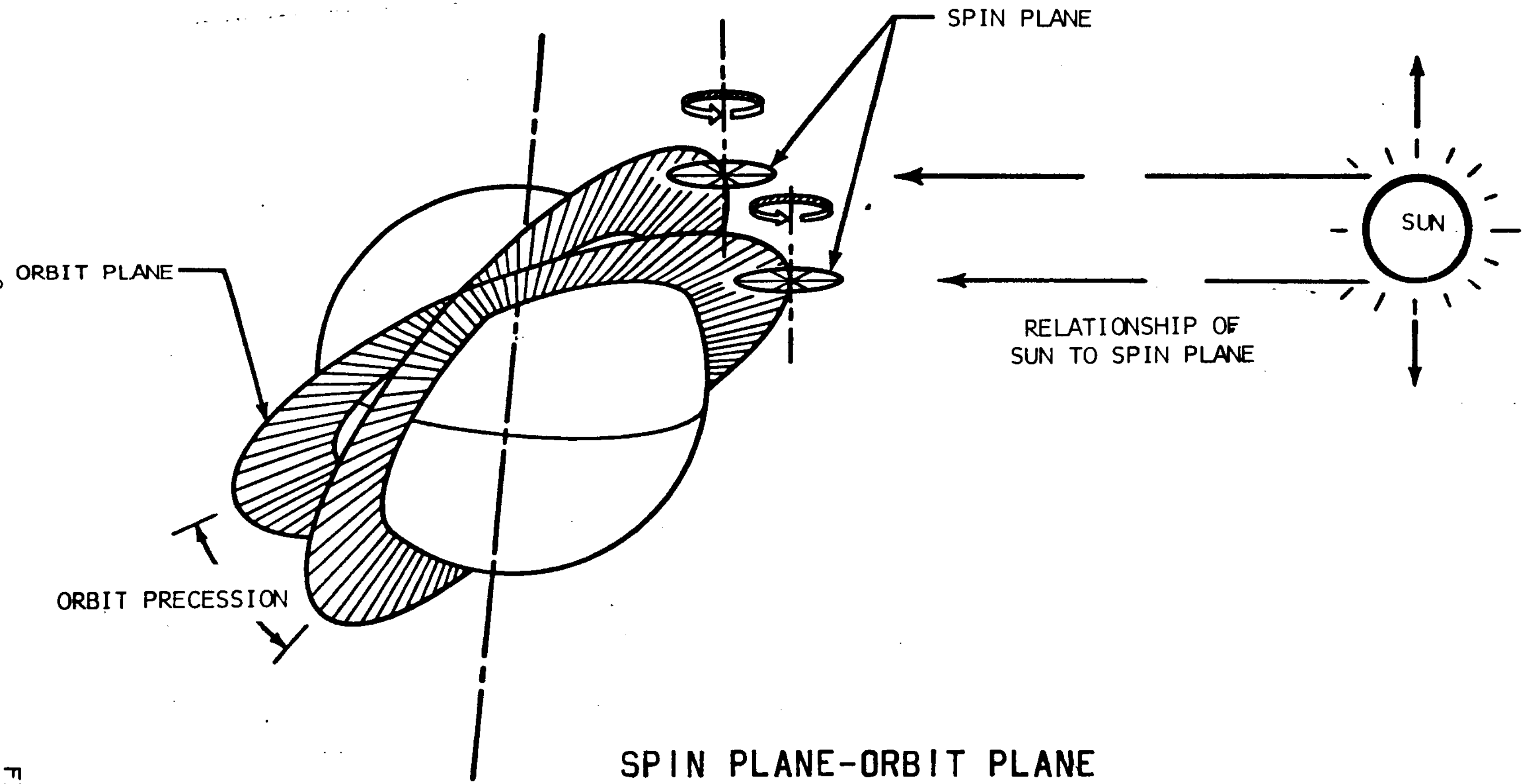
3  FORWARD END OF EXPERIMENT MODULE SHADOWED BY S IV B

4  SIDE TOWARD SUN COMPLETELY ILLUMINATED



COMMAND-SERVICE MODULE THERMAL CONSIDERATIONS

FIGURE 8.1



SPIN PLANE-ORBIT PLANE
SUN RELATIONSHIP

FIGURE 8.2

such that the "g" level previously defined (.3g) is established at the crew compartment. We may logically divide the functional requirements into three phases: prespin, spin-up, and steady state spin phase. These phases are defined respectively as the period prior to the initiation of the spin-up maneuver, the portion of the mission in which the rate is being increased from zero to the spin rate value of approximately 3.4 RPM, and the portion of the mission from spin-up to experiment termination. The durations of these phases are typically $\frac{1}{2}$ day, 1 day, and 10 days, respectively. Another phase, separation and deorbit, creates no requirements different from the Apollo mission.

The control requirements may be separated by function and by phase. The functional requirements are rate stabilization, attitude stabilization, balancing, and maneuvering. The philosophy used here is that maneuvering will be performed only in the nonspin phase. The spin phase requirements are rate and attitude stabilization, and balancing. Since the external torques(aerodynamic and gravity gradient) tend to average out and introduce only small bias angular momentum components relative to the momentum of this vehicle, the vehicle has intrinsic attitude stability when spinning and the primary requirements in the spin phase are rate stabilization and balancing.

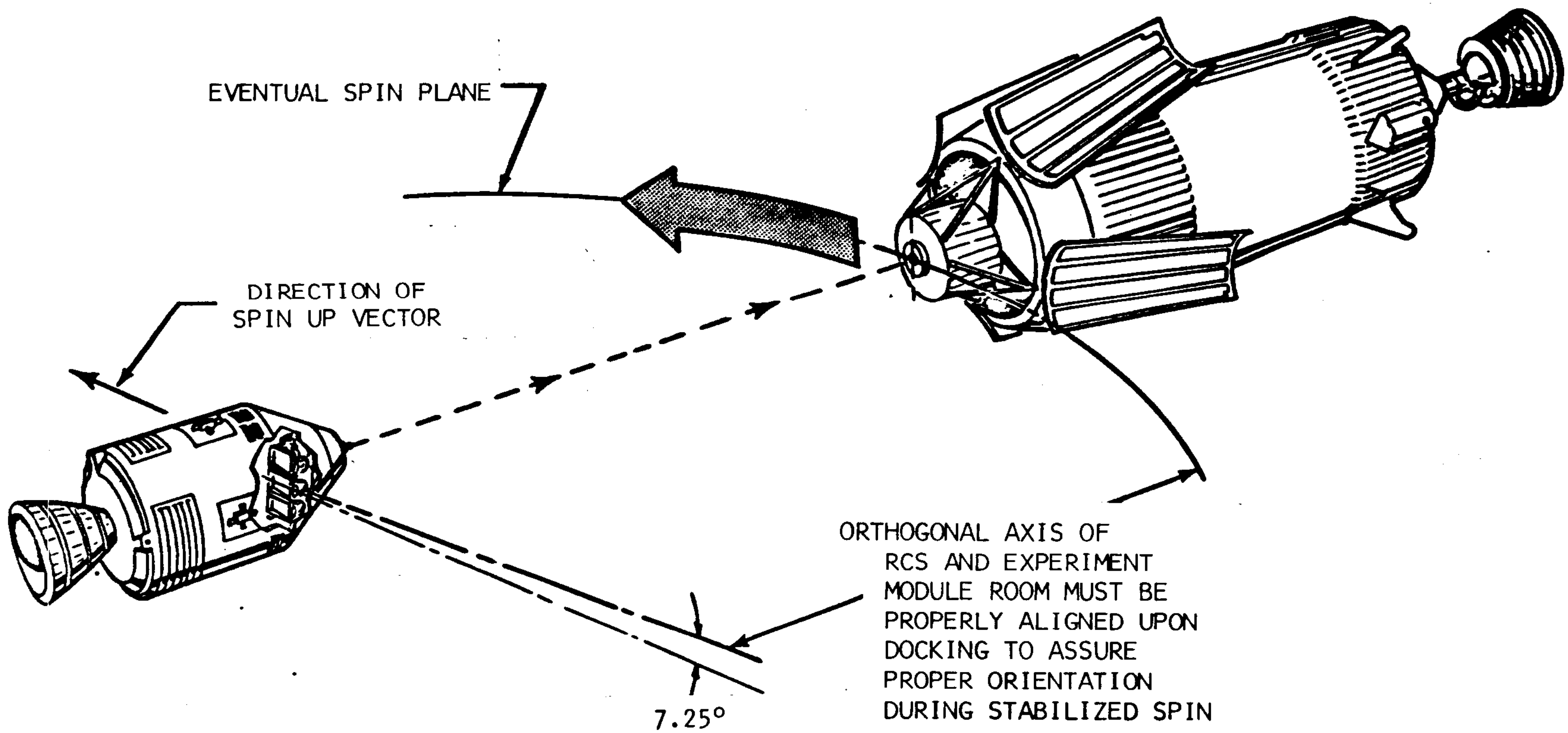
8.2.1 Pre-Spin and Separation Phases

The G&C functional requirements for the pre-spin phase are basically the same as Apollo. There is no new programming or hardware required for this phase; the new requirement for this mission is that of a specific sun orientation which requires maneuvering to a pre-determined attitude and introduces no new requirements compared to Apollo. This may be performed automatically with the Command Module Computer (CMC) or manually with the CMC or Stabilization and Control System(SCS). The main problems in this phase are operational in that the CSM must be properly aligned with the experiment module and S-IVB. See Figure 8.3.

The separation phase and subsequent mission functions are similar to Apollo operations and introduce no new requirements.

8.2.2 Spin-Up Phase

It is this phase, with the steady state phase discussed in the next paragraph, which creates the greatest impact on Apollo systems. The requirements as defined in other sections of this report specify a spin rate of 3.4 RPM or equivalently a gravity level of .3g. It has been further specified by the experimenters that the spin-up phase be accomplished over 24 hours.



VEHICLES-SPIN PLANE
RELATIONSHIP

FIGURE 8.3

8.2.3 Steady State Spin Phase

The requirements in the steady state spin phase are to maintain the spin rate about the y CSM axis at 3.4 RPM $\pm$ .05 RPM for up to 10 days. The rates about the other axes are to be maintained at zero $\pm$ .05 RPM. This corresponds to an artificial gravity level of .3g and a tolerance of $\pm$ .01g. The attitude of the spin vector should be maintained normal to the sun line to $\pm$ 10 degrees. This mode introduces new requirements from Apollo in that different control logic is required for control of a spinning body such as this.

Also, the duration of the mission requires a means of rate damping other than that of the RCS jets due to the propellant capacity problem.

8.3 ANALYSIS

This section presents the analysis and simulations performed to establish the system feasibility and define a preliminary G&D system. The Moby Dick configuration and the cable connected vehicle were considered. The analytical results described herein are:

a. System analysis to define the system configuration.
b. Simulation to establish system parameters and magnitudes and demonstrate feasibility of control systems and operational philosophy.

8.3.1 Operational Analysis

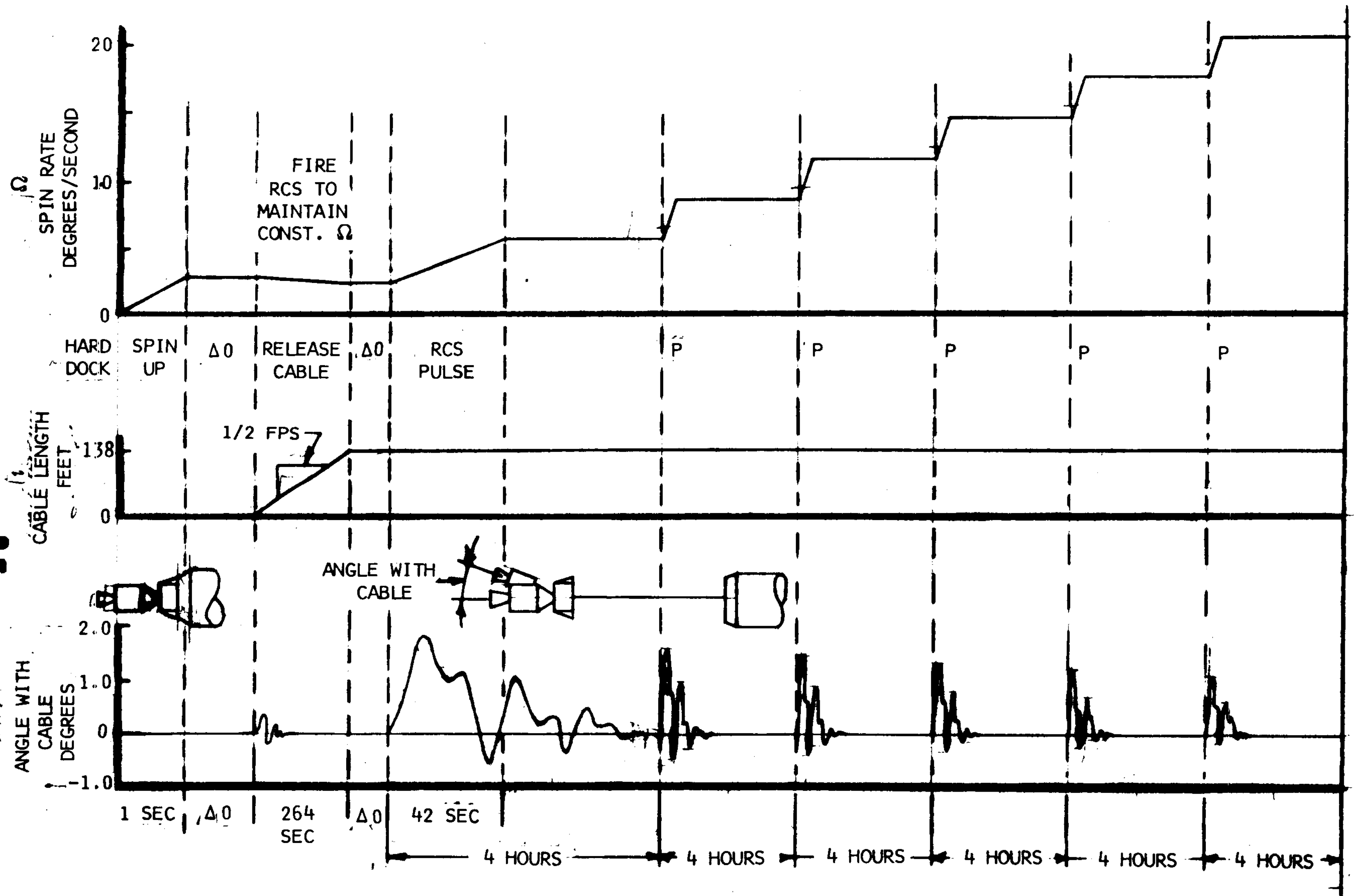
The operational analysis performed thus far consists of defining the spin-up timeline, spin-up philosophy, and propellant budget.

8.3.1.1 Mission Spin-Up Timeline

The timeline for phases other than spin-up and experiment are similar to the Apollo earth orbital missions and are not repeated. The spin-up timeline is determined from the experiment duration, the specification of a 24 hour spin-up requirement, and technical factors. The justification of these times is based on the experimental requirements specified in other sections. The timeline from spin-up initiation to steady state (3.4 RPM) is given in Figure 8.4.

8.3.1.2 Spin-up Propellant

It is desired to determine the best method of spinning up two bodies connected by a cable such that the distance between the centers of gravity of the two bodies is variable.



Δ0 = OPERATIONS TIME

SPIN UP PROFILE

FIGURE 8.4

1. Spin up to rate ω_D with the vehicle in the docked position such that when the final separation distance l_f is achieved, the rate will be a specified value ω_1. The vehicle is then spun-up in the fully deployed configuration from ω_1 to the required final spin rate ω_f.
2. Spin-up to a value ω_D such that when the vehicle is deployed to l_f the spin rate is ω_f.
3. Spin-up to some rate ω_1, in the docked configuration. Deploy the vehicles to l_f maintaining the rate constant at ω_1. Spin-up to the final spin rate ω_f.

Considering 1, the RCS propellant required for spin-up is a minimum when $\omega_1 = 0$ (i.e., the vehicles deploy with zero angular rate followed by spin-up in the fully deployed configuration from zero to the required final spin rate ω_f).

Case 1 is always superior to Case 2.

Minimum Case 1 is superior to Case 3 from the standpoint of RCS propellant consumption. From an operational standpoint, however, it is considered best to deploy with a small angular rate. We conclude, therefore, that Case 3 is the preferred method with the added recommendation that the angular rate during deployment be kept as small as possible.

The total propellant for Case 3 consists of the amount required to maintain the spin rate at ω_1 while deploying, and the amount required to spin-up to ω_f from ω_1 in the fully deployed configuration. The total propellant required is given by:

$$W = \frac{2\omega_1 Me(l-l_D)}{M_R I_{sp}} - \frac{2\omega_1 MeJ}{M_R\, I_{sp}} \ln \frac{J + M_R\, L}{J + M_R l_D} + K_p \frac{I_D}{(J + M_R l_D)} \omega_1 + K_p \frac{I_f}{(J + M_R\, l_f)} (\omega_f - \omega_1)$$

where:

M_1 = Mass of vehicle number 1 (slugs)

M_2 = Mass of vehicle number 2 (slugs)

I_D = Moment of inertia of docked configuration (slug ft^2)

I_f = Moment of inertia of fully deployed configuration (slug ft^2)

I_D = Distance between c.g.'s in docked configuration (ft)

I = Distance between c.g.'s in fully deployed configuration (ft)

J = Moment arm between RCS and c.g. of vehicle number 1 (ft)

$$M_e = \frac{M_1 M_2}{M_1 + M_2} \quad \text{(slugs)}$$

$$M_R = \frac{M_2}{M_1 + M_2}$$

I_{sp} = Specific impulse of RCS engine(sec)

$$K_p = \frac{1}{57.3\, I_{sp}} \quad \left(\frac{\text{rad}}{\text{deg sec}}\right)$$

ω = Angular velocity (rad/sec)

Note: $K_p \omega \longrightarrow$ Units of ω are deg/sec

We now consider the RCS propellant required for spin-up for the cable connected Experiment Module Configuration to .347 rad/sec with deployment at a constant spin rate of .05 rad/sec.

Weight, moments of inertia, etc., for this configuration are:

W_1 = 31,427 pounds

W_2 = 32,298 pounds

M_1 = 978 slugs

M_2 = 1,003 slugs

I_1 = 137,000 slug ft^2

I_2 = 323,000 slug ft^2

I_{sp} = 278 sec

J = 6.5 ft

l_D = 46.3 ft

l = 179 ft

Using these figures, 9.2 lb of propellant are required to spin-up to .05 rad/sec in the docked configuration, 41.2 lb to maintain spin rate of .05 rad/sec during deployment, and 180 lb to spin-up to .35 rad/sec in the fully deployed configuration, making a total of 230.4 lb. It was determined from simulation that an additional jet should be fired in the -X direction to keep the angle between the cable and the spacecraft below 5 degrees; therefore, propellant for the .05 to .35 rad/sec phase is increased by 50%, or 90 lb. An additional amount is required for rate damping in the hold phases of 50 lbs. Therefore, the total allotment for spin-up is 370 lbs.

8.3.1.3 Mission Propellant Budget

The Reaction Control System (RCS) propellant required for other phases of the mission has been obtained from similar Apollo budgets. The spin phase budget was given in the previous paragraph. The resulting budget is presented in Table 8.1.

8.3.2 <u>Moby Dick Simulation Results</u>

Presented herein are some of the results of the analog study of the AAP "Moby Dick" configuration MD-3 spin mode control system.

The objective of this study was to determine the ability of the CMG-RCS combination to perform attitude control in the spin-up and steady state spin phases of the mission.

To establish an artificial gravity equal to .3g at the crew compartment parallel to the X_B-Z_B plane, and located at Ly from the center of mass of the configuration(shown in Figure 8.5), the vehicle must maintain an angular rate of $\omega^2 = .3g/Ly$ directed along the Z_B axis. The Z_B axis was chosen as the vehicle spin axis to obtain passive stability ($I_{ZZ} > I_{XX}$). (Note the axis system definition in Figure 8.5 as opposed to CSM coordinates.) The Control Moment Gyro spin axis was oriented along the Z_B axis as shown in Figure 8.6.

The general rigid body equations of motion were used in the simulation. Inertia coupling was included in order to study its significance in the spin modes.

The vehicle inertia properties used in the simulation were:

I_{XX} = 1,522,68.2 slug ft^2
I_{YY} = 26,557.4 slug ft^2
I_{ZZ} = 1,623,929.5 slug ft^2
I_{XY} = -11,058 slug ft^2
I_{YZ} = 2,227 slug ft^2
I_{XZ} = -52.4 slug ft^2

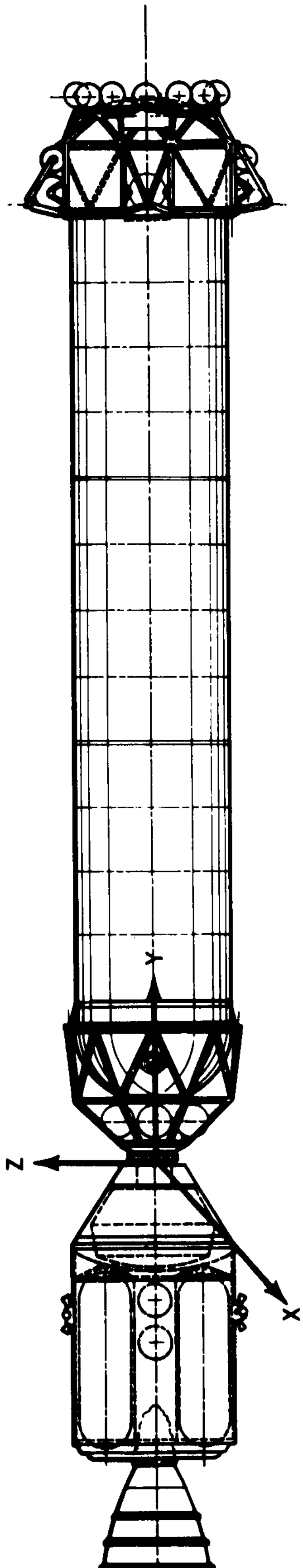
8.3.2.1 Spin Mode Control System

A flow diagram of the spin control configuration is given in Figure 8.7A. The Reaction Control System simulated had a rate deadband of .2 deg/sec. The control moment transformation in the simulation included cross coupling in the control axes due to RCS jet offset of $7\frac{1}{4}$ degrees.

ESTIMATED SM RCS PROPELLANT BUDGET

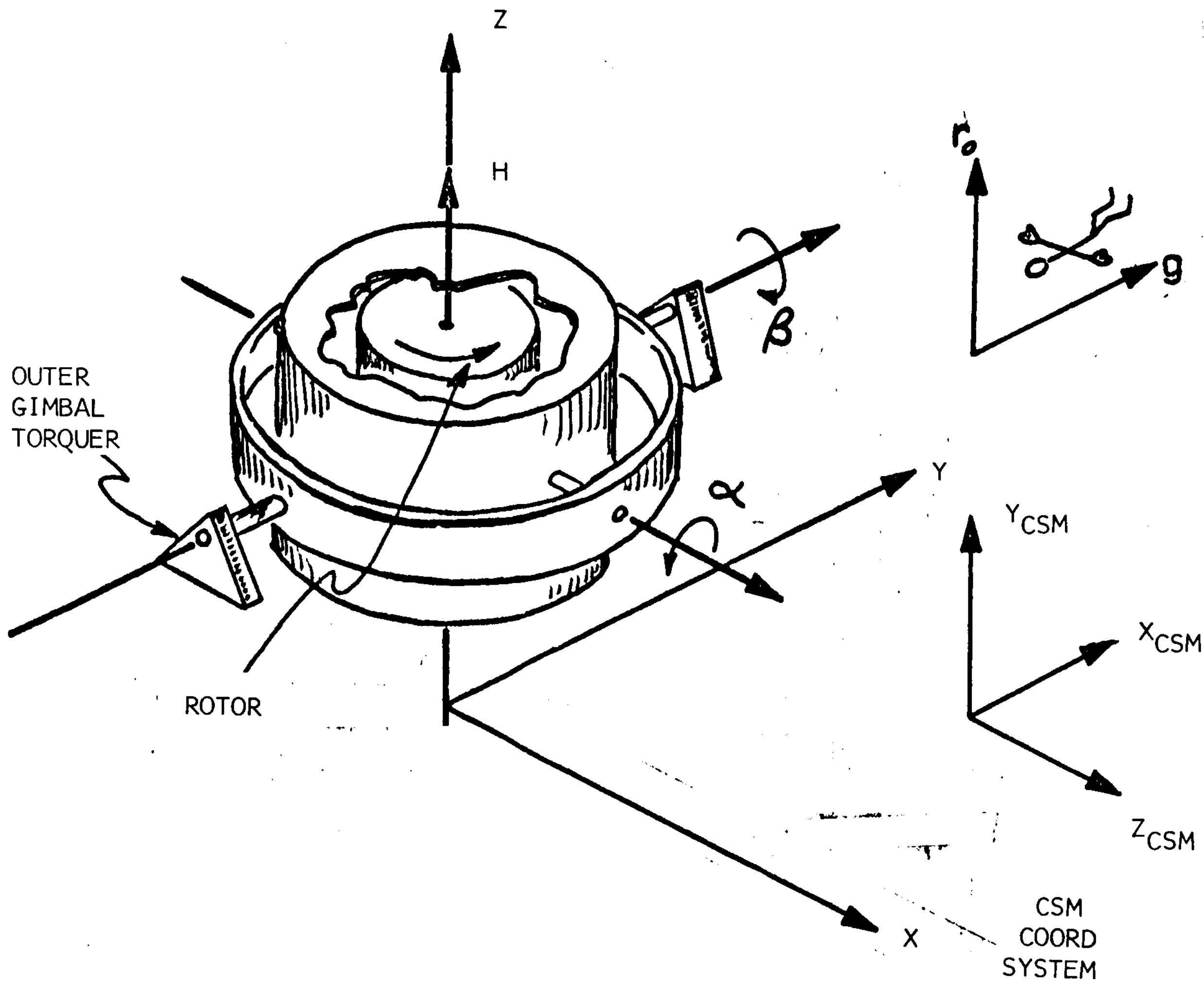
MAXIMUM PROPELLANT LOADED	1348 POUNDS
UNUSABLE	- 31
MIXTURE RATIO UNCERTAINTY	- 46
GAUGING ACCURACY	- 28
SM RCS DEORBIT	-528
AVAILABLE FOR MISSION	723
PRELAUNCH CHECK	- 5
TRANSPOSITION AND DOCKING	- 49
SPS BURN (CIRCULARIZATION)	- 24
POST-BURN TRIM (V = 7 FPS)	- 50
ORIENTATION AND IMU ALIGNMENT	- 2
SPIN-UP	-370
ANGULAR VELOCITY CORRECTIONS	-100
CMG DESATURATION	- 10
DESPIN (CSM ONLY)	- 10
SPS BURN (DEORBIT)	- 25
REENTRY ORIENTATION AND SEPARATION	- 27
MARGIN	51

TABLE 8.1



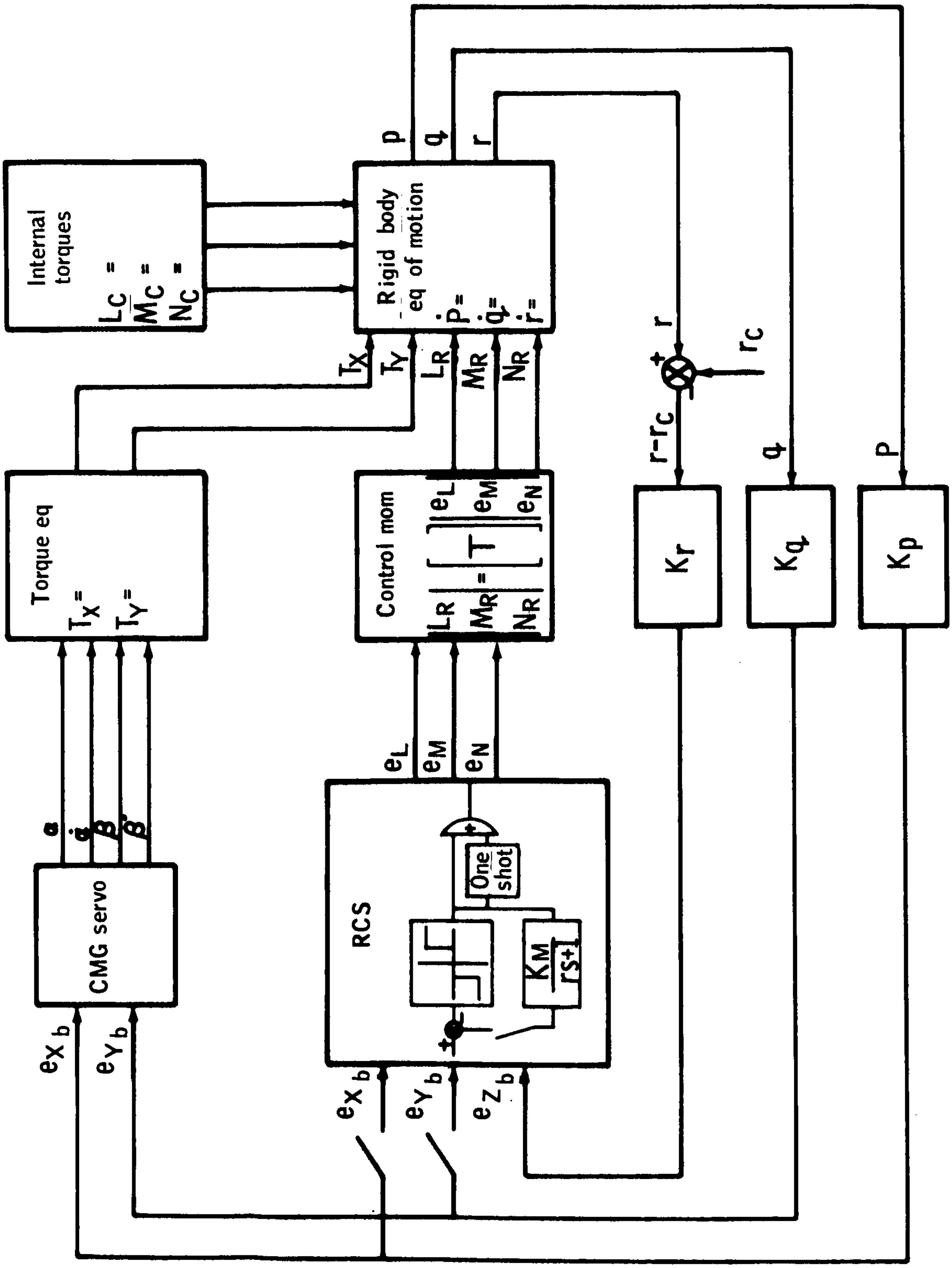
MOBY DICK CONFIGURATION MD-3

FIGURE 8.5



CMG DEFINITION

FIGURE 8.6



SPIN RATE MODE

FIGURE 8.7 A

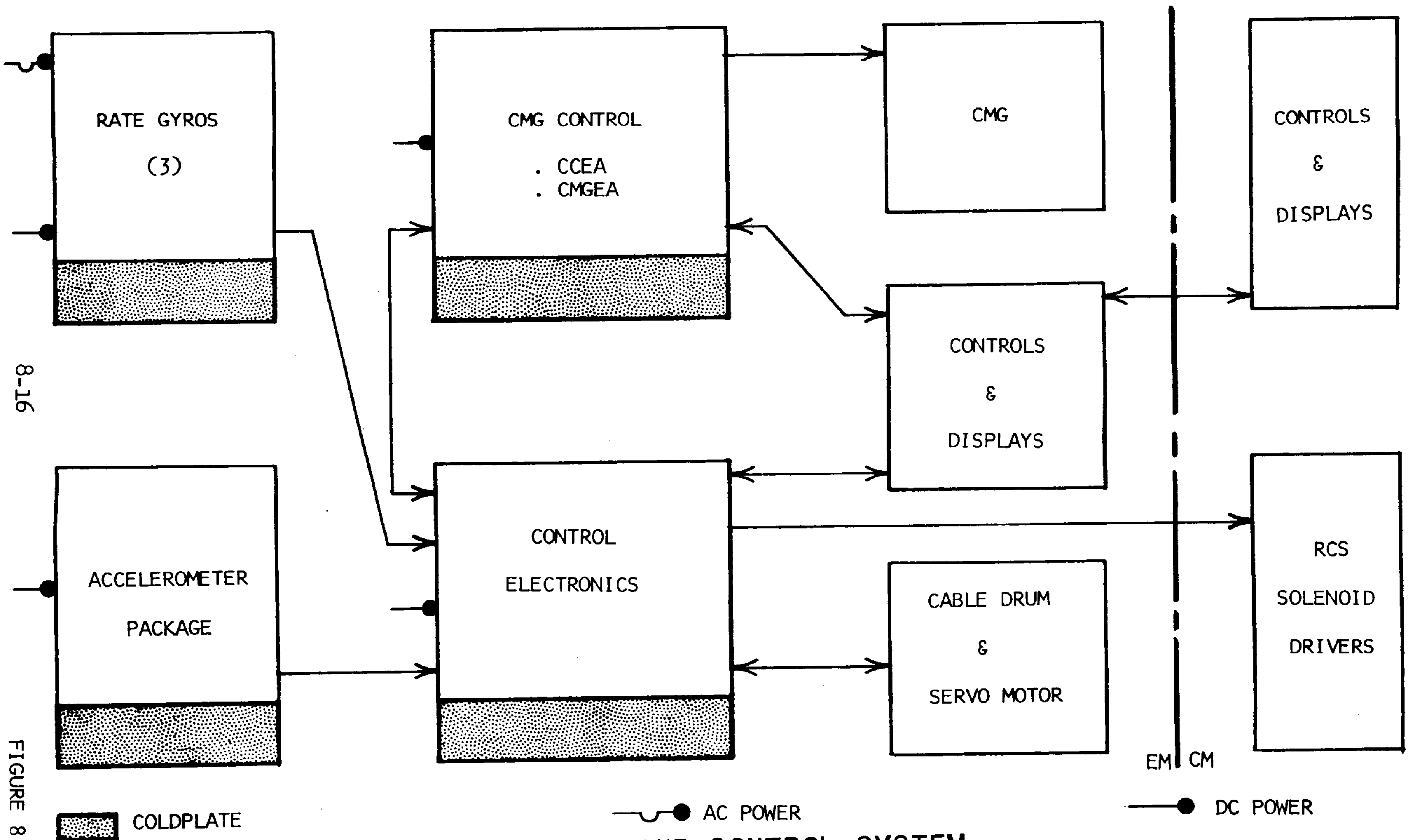
The control system shown on Figure 8.7B provides for the constant spin mode and may be designed to include the spin up mode. The CSM G&N system could provide control during the cable deployment and spin up by re-programming in the digital autopilot. The cable deployment system consists of a drum and servomotor and can be controlled both manually and automatically. The CMG control accepts torque commands from the control electronics and torques the CMG gimbals. The CMG control contains the CCEA(Control Computer Electronic Assembly), CMG EA(CMG Electronic Assembly), and its own power supplies. The CCEA computes the CMG control law and performs Euler angle resolutions of CMG momentum vectors. The CMG EA contains the electronics for the CMG gimbal rate servos and CMG spin motor control.

The control system contains one control moment gyro of the Langley-Marshall ATM type(2,000 ft-lb-sec) to provide wobble damping in two axes, X and Z. Nominal spin direction of the CMG is parallel to the experiment spin vector. Pitch rate damping is provided by Service Module RCS engines. Spin rate torques are provided by RCS ±Z translation engines. Correct attitudes are obtained by driving X and Z rate component after correct attitude alinement. The three acceleromenters indicate g-vector and out-of-plane wobbling. The out-of-spin plane oscillations about the combined c.g. of the two vehicles will be damped by SM RCS translation engines.

The total auxiliary system (not including cable deployment system) weight is 609.5 pounds. System power is 368 watts nominal and 790 watts peak. System volume is 18.87 cu. ft. The CMG and CMG electronics alone account for 560 lbs. and 18.2 cu. ft. If a smaller unit, the LRC 1,000 ft-lb-sec CMG can be used, the weight will be approximately 143 lbs. less.

8.3.2.2 Simulation Results

The rigid body equations of motion were solved on an analog computer which allowed variation of the constants and control feedback laws to simulate various control modes. A number of runs were made on the "Moby Dick" configuration MD-3 to explore the effects of variations in the parameters which affect the controllability. The steady state spin phase and the transient spin-up phase were studied. Control loop feedback gains and control moment gyro size were varied to find acceptable combinations which are within the gyro saturation limit. It was desired to find if RCS control in the non-spin axes (X, Y) was required in the spin up phase; therefore, performance with and without RCS control was determined by computer runs. The disturbances due to man motion were simulated as an impulsive rate for impulsive motion and as a ramp torque up to a constant value for out of plane or cross product imbalance. The impulsive disturbance is obtained from the maximum amount of energy a 6 slug man can impart to the spacecraft. The magnitude of the



STABILIZATION AND CONTROL SYSTEM

FIGURE 8.7B

torque due to cross product imbalance is obtained from the maximum excursion of 1 or 2 men from the center, i.e., $T_x = MYZr^2$.

To determine the control feedback gains and gyro size required, these values were varied and the time to damp to $^1/_e$ times the initial value of p or q(i.e., the time constant). The time constant was used as a performance measure. The maximum gain which can be used for this configuration was calculated to be 50. The analog study attempted to find a set of gains and CMG size with gains less than this value. The set of control parameters chosen were as follows:

$$\text{CMG angular momentum (H)} = 2000 \ \frac{\text{slug ft}^2}{\text{sec}}$$

$$\text{Rate feedback gains:} \quad K_p = 12.5, \ K_q = 12.5, \ K_r = 1$$

8.3.2.3 Results

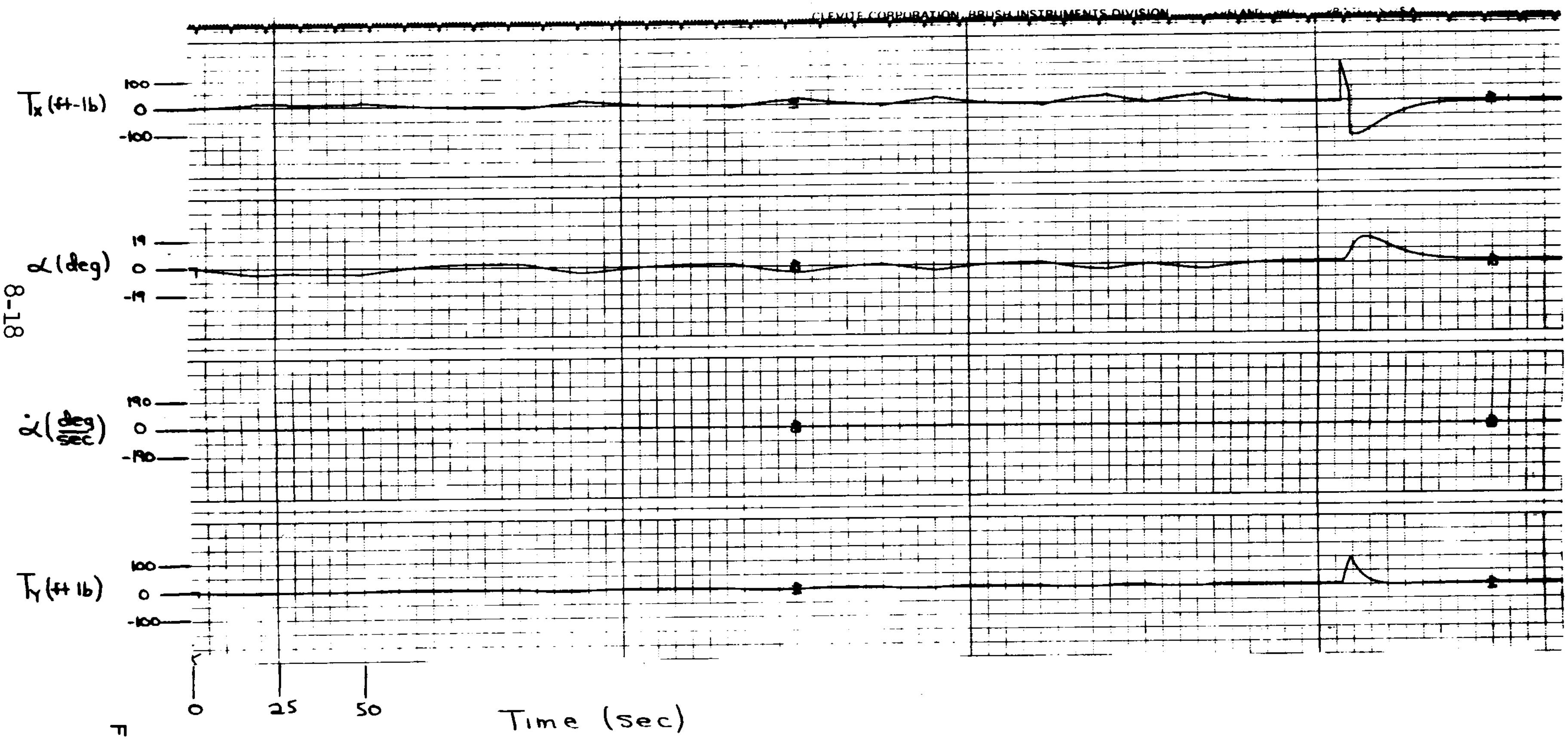
The vehicle response in terms of certain dynamic variables which are defined herein is presented in Figure 8.8. The case presented shows the spin-up phase and the response to an impulsive disturbance in the steady state phase. The RCS was not activated in the X and Y channels for this run through spin-up. It is therefore a good illustration of the CMG performance. A definition of the variables presented is given:

T_x - ft - lb	CMG torque along X_b axis
T_y - ft - lb	CMG torque along Y_b axis
α - deg	Inner gimbal angle of control moment gyro
$\dot{\alpha}$ - deg/sec	Rate of change of inner gimbal angle
β - deg	Outer gimbal angle of control moment gyro
$\dot{\beta}$ - deg/sec	Rate of change of outer gimbal angle
p - deg/sec	Angular rate about X_b axis
q - deg/sec	Angular rate about Y_b axis
r - deg/sec	Angular rate about Z_b axis
γ_3 - deg	Direction cosine between Z body axis and Z inertial reference(one minus γ_3 is printed out)
F_N - lb	RCS thrust
WP - lb	RCS total propellant consumption

8.3.2.4 Concluding Remarks

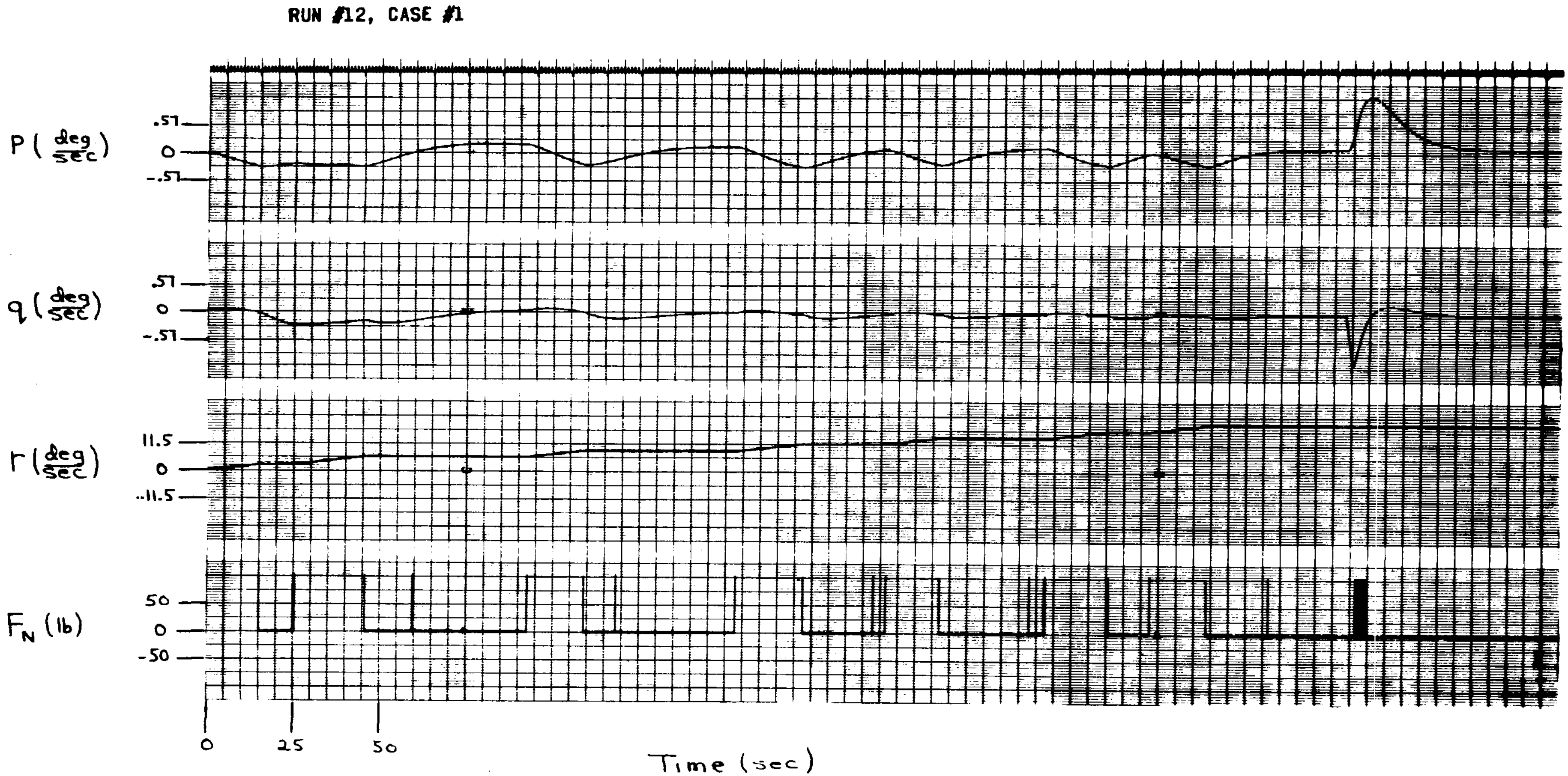
This study has established the mode of CMG control for the spin experiment, the CMG size, and gains to provide rate stabilization. Additional simulation will be required to establish

RUN #12, CASE #1



VEHICLE RESPONSE

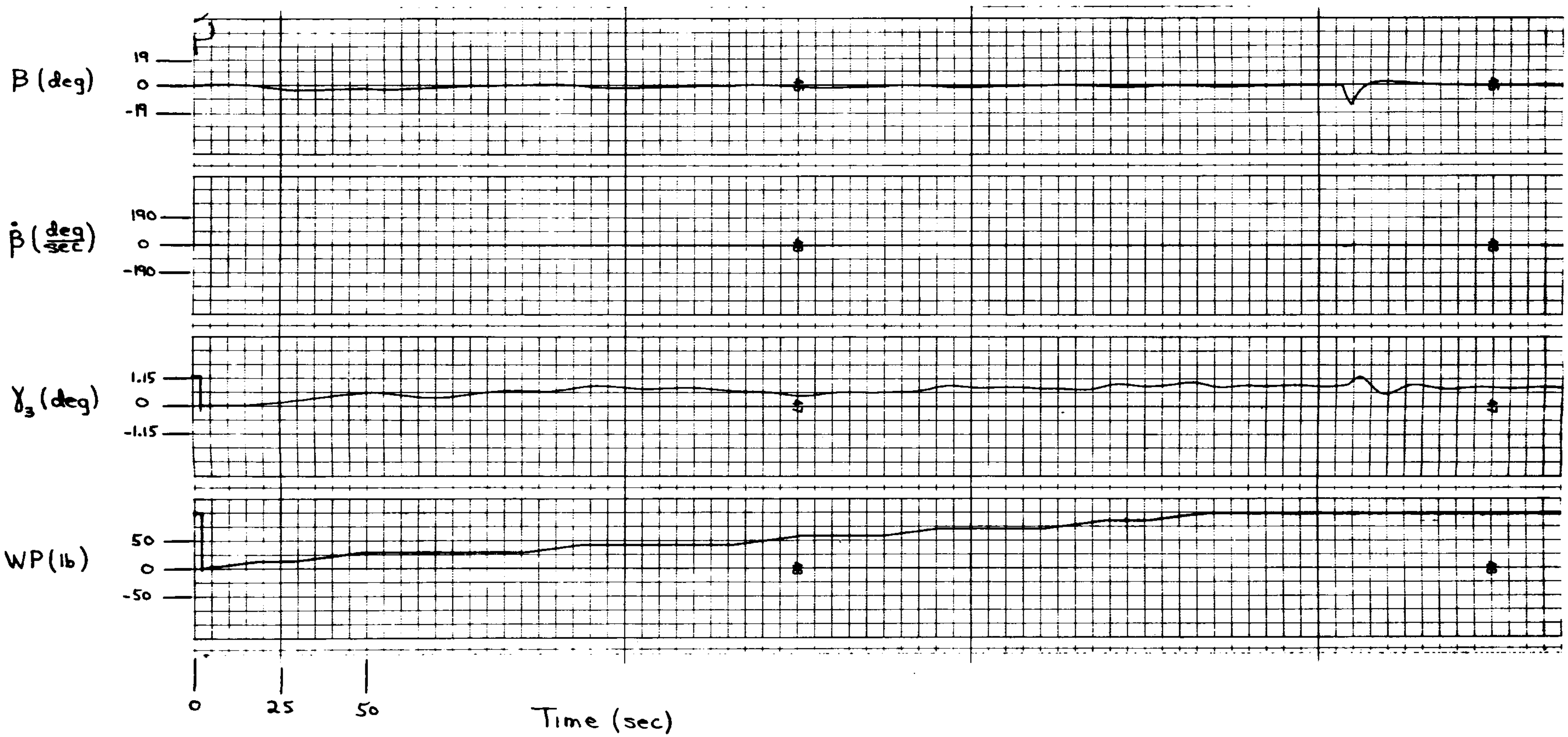
FIGURE 8.8A



VEHICLE RESPONSE

FIGURE 8.8B

RUN #12, CASE #1



VEHICLE RESPONSE

FIGURE 8.8C

attitude maneuver techniques. The control mode required is indicated in Figure 8.7A. RCS control should be used in all axes in spin-up and de-spin. In the steady state spin phase, RCS control is used in the spin axis and the CMG controls the non-spin axes. Two CMG's may be provided for redundancy, but are not required for control.

The CMG size required is as given previously as H = 2,000 ft-lb-sec. The gains for the non-spin axes control were chosen to be $K_p = K_q = 12.5$. The RCS deadband in the spin axis controller was 0.2 deg/sec, which appears adequate; however, this parameter was not studied. The SCS-RCS jet logic must be changed to provide the 23 ft. lever arm. With this lever arm, the RCS propellant required for the spin experiment will be less than 300 lbs. The simple control law:

$$e_x = K_p P$$

$$e_y = K_q Q$$

with the CMG servo operating in a position servo mode, i.e.,

$\alpha \approx e_x$ and $\beta \approx e_y$ is a feasible control technique for the spin-up, de-spin, and steady state spin phases.

The operational procedure recommended is to actuate CMG and RCS systems prior to spin-up. Switch systems to spin mode with the RCS actuated in all channels as shown in Figure 8.7A. Input spin rate command r_c in steps. The spin-up may be accomplished over the 24-hour period, as specified. To obtain additional results for the Moby Dick study, refer to MSC Internal Note 67-EG-33.

8.3.2 System Analysis

The control system required to perform the artificial gravity experiment may be broken into subsystems which include:

1. Sensors which sense the vehicle motion, e.g., rate gyros and accelerometers.
2. Control computer which performs the computation on the sensed information, control, laws, and logical switching.
3. Actuators which provide torques to the vehicle to effect control.
4. Displays.

The choice of the system required to provide artificial "g" control includes this selection components. It must include present Apollo hardware as much as possible. However, to minimize the impact on Apollo system reliability, it is desired to maintain minimum interface with Apollo subsystems. Thus, it is probably better to include total systems rather than single components which interface with Apollo subsystem components.

Since the RCS propellant required to control all axes for this mission would exceed the Apollo tank capacity, it is necessary to add an actuator suitable to long-term operation in the presence of cyclic torques.

The actuator which has been shown to be superior for the required rate damping is the control moment gyro (CMG). Since MSFC is developing a gyro of the 2,000 ft-lb-sec size and LRL has a gyro of 1,000 ft-lb-sec size, these two sizes were considered in this study. Preference is given to 2,000 ft-lb-sec wheel since it is undergoing a full engineering development program.

Reaction jets are required to provide spin rate controls and are also necessary for non-spin axis control of the cable-connected vehicle (CCV) in the steady-state spin phase. The actuator system required is therefore a dual CMG and RCS system.

The required sensors for CCV rate damping are three rate gyros and three accelerometers. It was assumed that the attitude constraint is ± 10 degrees and that passive attitude control will meet this requirement. If this proves not to be the case, an attitude sensor may be added. The logical choice would be a set of sun sensors.

The control logic required for a spinning body is different from that of Apollo and the CMG control requires a new system; therefore, a new control computer is required.

The two control modes which must be added for this experiment are spin-up and steady-state. The present CMG control system could be modified to provide the spin-up mode or it can be included in the spin control system to be added. Manual spin-up is also possible. At any rate, a new spin control system is required which has the following components:

a. Sensors
   1. Rate gyros in X, Y, Z axes
   2. Accelerometers in X, Y, Z axes

b. Actuators
   1. One Control Moment Gyro (CMG) (2,000 ft-lb-sec) with axes mounted parallel to tye Y axis of the CSM
   2. All CSM RCS jets will be used with logic different from Apollo logic.

c. Control Computer
   1. An electronic package may be installed in the experiment module to supply signals to the RCS jets and the CMG for steady-state operation.

d. Displays

This system may be added as integral unit to the experiment module with interfaces to the RCS jet drivers. Although RCS control is required in all axes, the primary control in the non-spin axes(the CSM X and Z axes) is provided by the CMG while the RCS provides the spin axis control(CSM Y axis) supplemented by passive damping. The Moby Dick configuration requires only this primary control; however, the cable connected vehicle requires, because of the added degrees of freedom of the vehicle with respect to the cable, the RCS jets in all axes. An alternative to inclusion of RCS jets in all axes of the automatic system would be continuous manual operation of all RCS jets with the translation and rotation hand controller; this does not seem operationally feasible.

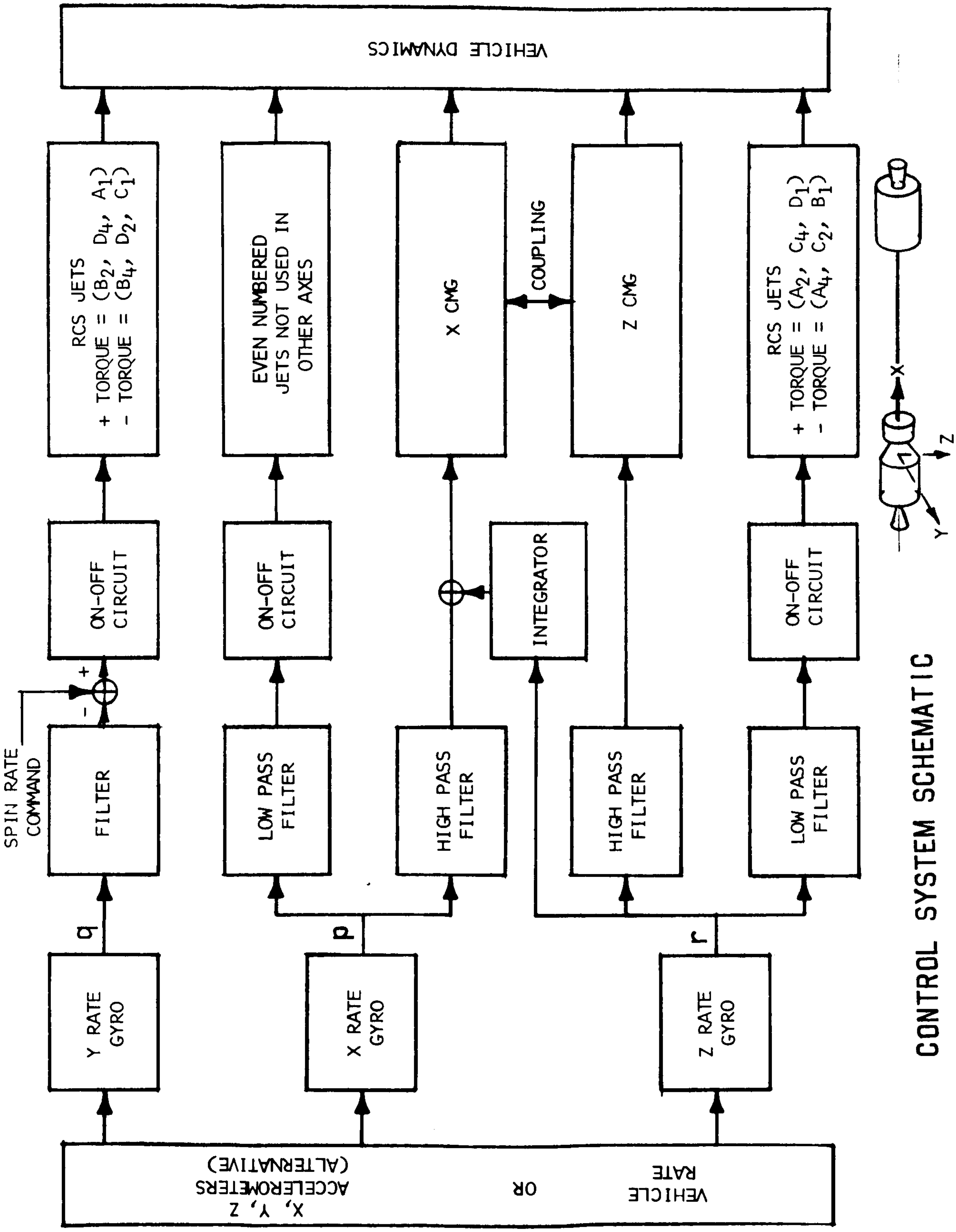
A flow schematic of the required control system is shown in Figure 8.9. The axes system referred to in the figure is CSM system shown in Figure 8.10 with the reaction jet locations. The basic concept of control is to use the CMG for small oscillations in X and Z and establish the ON-OFF circuits switching levels at some value safely below the CMG saturation levels. The spin rate(Y axis) is controlled by the RCS with an ON-OFF circuit set at a switching level compatible with the design requirement of .05 RPM accuracy. In addition, filtering is added to eliminate the low frequency signals from the CMG error signals and the high frequency components from the RCS error signals. The integration which integrates the Z axis rate and feeds into the X CMG error signal is to provide dynamic balancing in X, i.e., to maintain the Y axis parallel to the spin vector. The use of accelerometer information combined with rate gyro information is a possible alternative approach which should be given consideration in future study efforts.

8.3.3 Design Criteria

Presented in this section are considerations on the disturbances which effect the control system design. Significant torques which the control system must counteract are crew and equipment movement, gravity gradient, and aerodynamic.

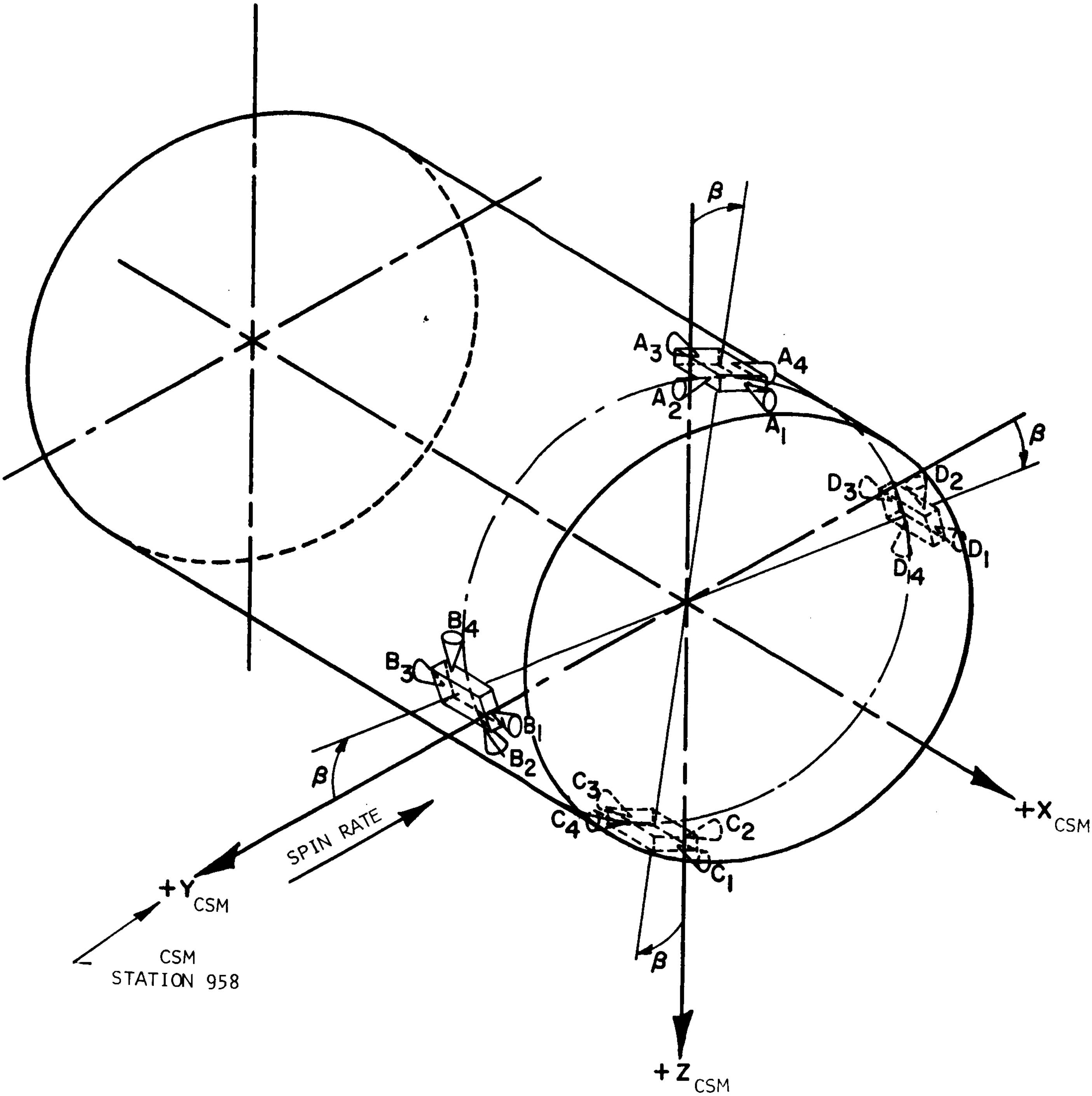
8.3.3.1 Crew Equipment Movement

This type of disturbance creates both mass unbalance and impulsive disturbances which the control system must counteract. The steady-state effect of the mass unbalance is to create an offset in the equilibrium position of the spacecraft with respect to the spin vector. This effect is apparent to the crew as a slight tilt of the floor with respect to the gravity vector. This effect is small for the CCV and is illustrated in Figure 8.11. Equipment movement effect can be minimized by moving equipment in opposition to maintain balance.



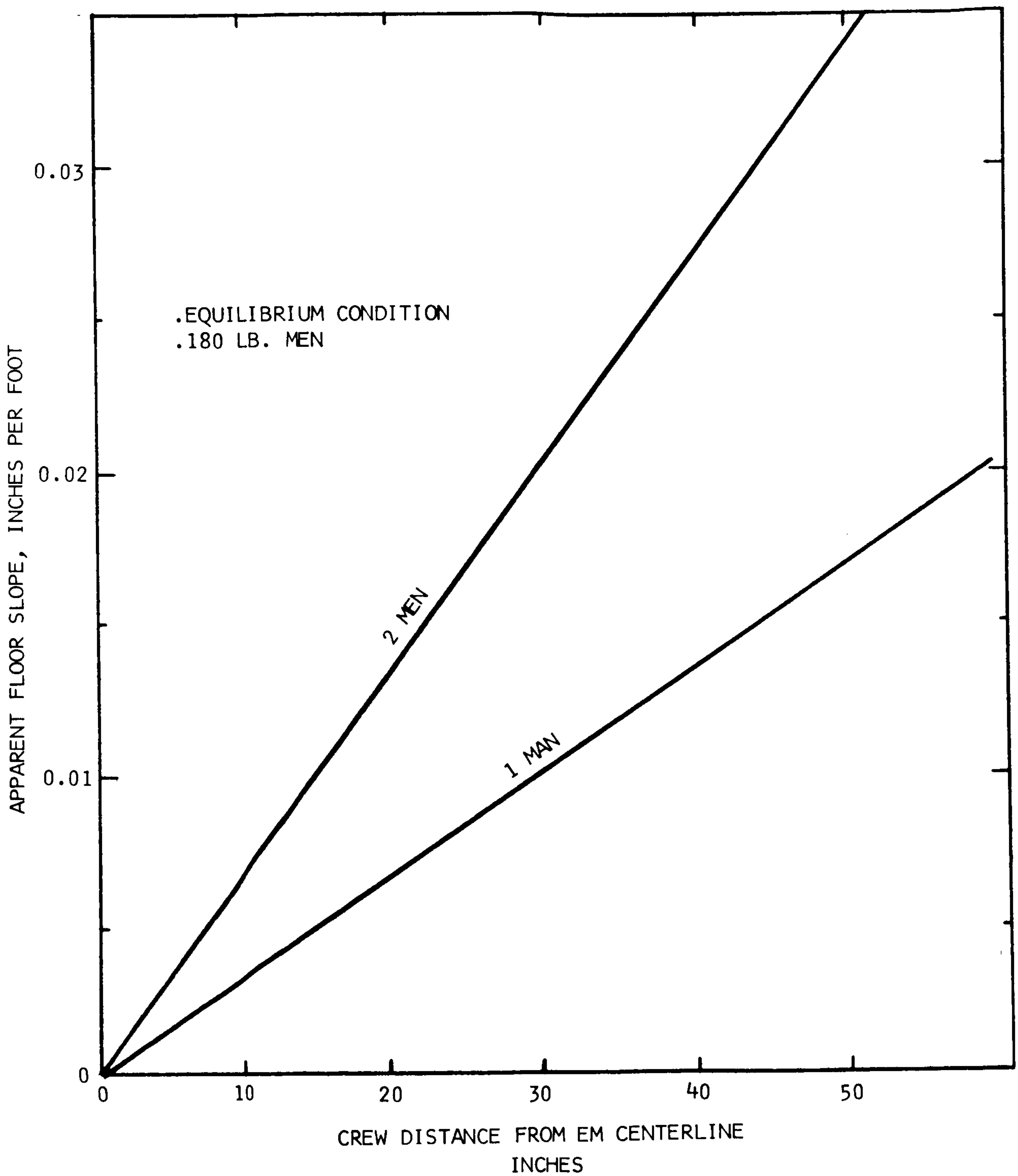
CONTROL SYSTEM SCHEMATIC

FIGURE 8.9



ENGINE LOCATION DIAGRAM

FIGURE 8.10



FLOOR SLOPE DUE TO CREW MOVEMENT

FIGURE 8.11

The effect of mass movement on the control system for both steady-state and transient conditions can be modeled approximately by a step disturbance torque. (The transient condition due to the step would be conservative.) The magnitude of this torque about the Z-axis for a spacecraft spinning about the Y-axis due to the movement of a 6 slug man from the center line of the experiment module(X-axis) to the outer wall of the experiment module along the Y-axis is found as follows. The experiment module is located 75 feet from the center of gravity(cg) and the spin rate is .35 rad/sec. The torque is given by $T_z = M\,XY\omega^2 = (6)(75)(5)(.35)^2 = 275$ ft-lb. Motions in other planes and their effect on the spacecraft are similar and are illustrated in Figure 8.12. Crew motion was also modeled as an impulsive disturbance which gives the spacecraft an initial rate. This is used to perform tradeoff studies on control system response vs control system gains and CMG size. Crew motion provides the most significant disturbance for the purposes of control system design.

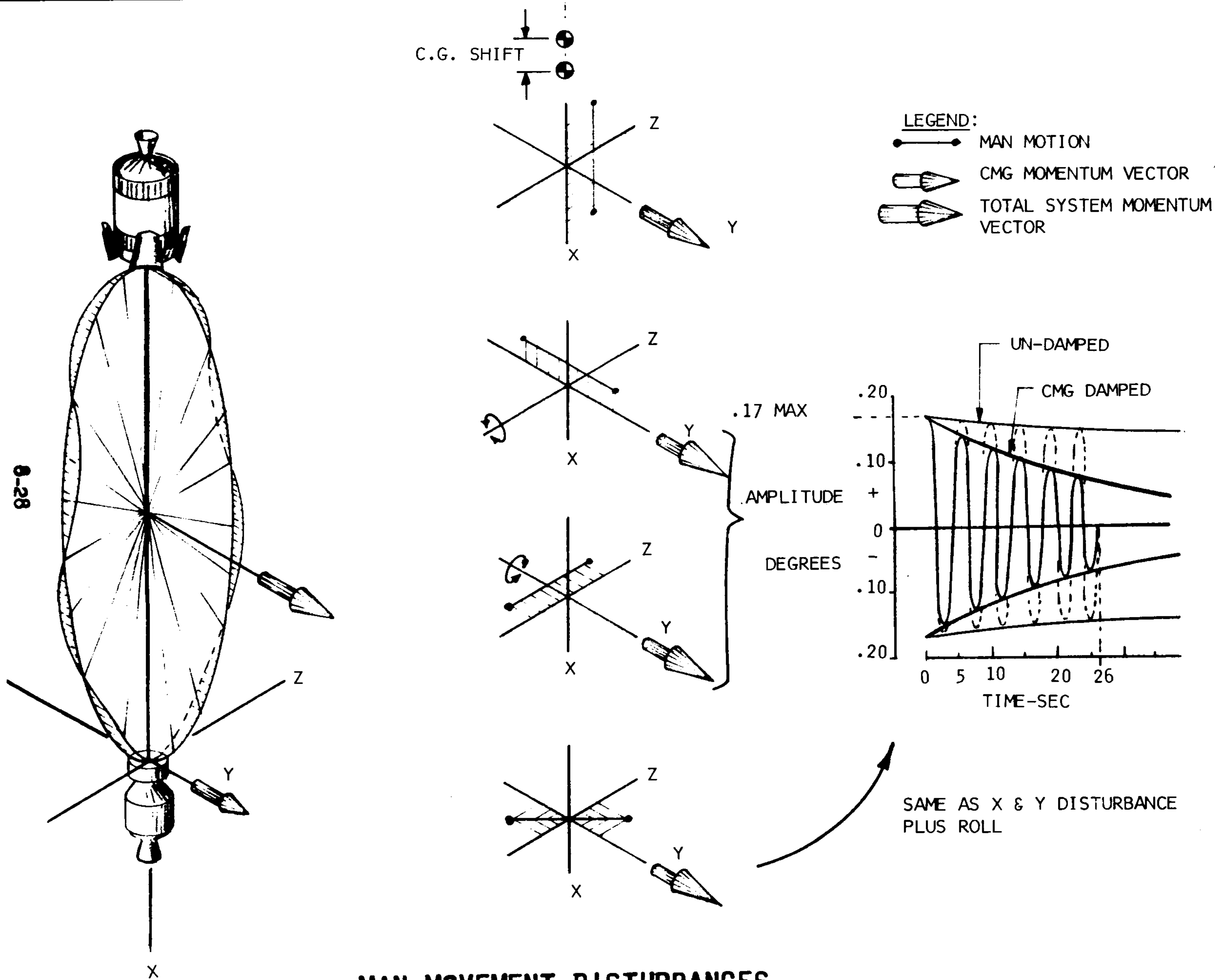
8.3.3.2 Gravity Gradient

The gravity gradient torque is a function of the square of the orbital frequency, the moments of inertia of the spacecraft, and the attitude of the spacecraft relative to the local vertical. The gravity gradient torque, therefore, acts cyclically on the vehicle at the spin frequency. It may have some small bias component which tends to precess the angular momentum vector of the vehicle, but this is small and can be neglected for control system design. Its effect should be considered in defining the attitude requirements for specific missions.

The maximum torque which would be experienced by the CCV at 132 NM would be on the order of 30 ft-lb. The torque on the Moby Dick at the same attitude would be approximately 3 ft-lb. These torques are well below the 275 ft-lb due to man motion.

8.3.3.3 Aerodynamic

The aerodynamic torque is a function of the attitude of the spacecraft with respect to the orbital velocity vector, the aerodynamic force coefficient, and the center of pressure(CP) location relative to the center of gravity(cg). The torque acts cyclically at spin speed and can be neglected in control system design for the CCV having a maximum value at 130 NM of 8 ft-lb. However, for the Moby Dick it is approximately 400 ft-lb. This is due to the large, light structure of the bag and the concentration of mass in the CSM causing a large distance between the center of pressure and the center of gravity. This would require the Moby Dick to be flown at a higher altitude to decrease this moment. The altitude under consideration when the analog study was conducted was 260 NM. This yielded a torque of approximately 1 ft-lb which is negligible.



MAN MOVEMENT DISTURBANCES

FIGURE 8.12

8.3.4 Control System Simulation

This section presents the results of linearized analysis, an analog simulation performed on a rigid vehicle with the inertia properties of Moby Dick MD-3, a digital simulation of the cable connected vehicle dynamics, and some passive damper analysis.

8.3.4.1 Linearized Analysis

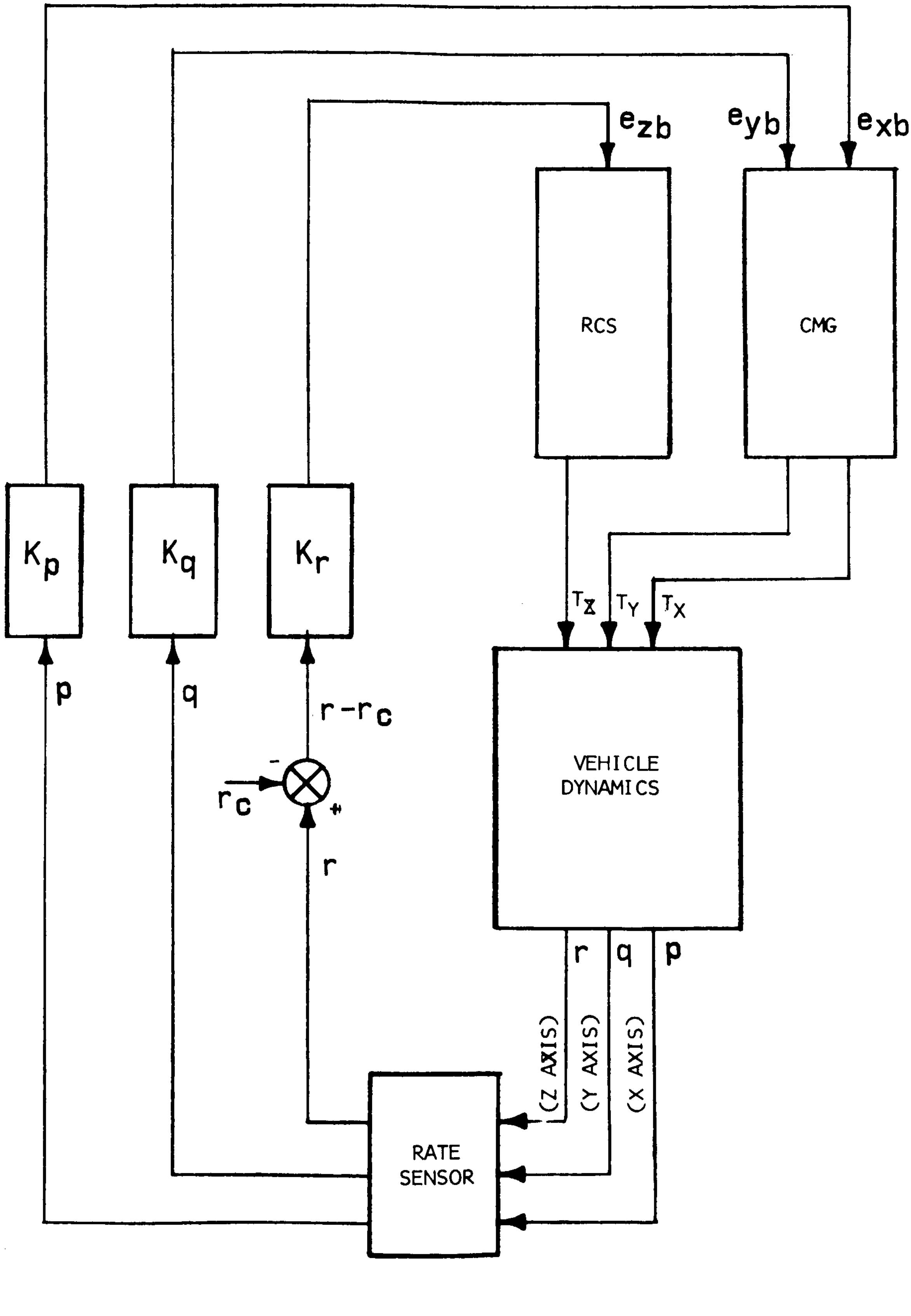
The linearized analysis defines the control system gains and control moment gyro size requirements. In prevsious sections the control requirements have been indicated as rate damping among others.

The rate damping function is that of maintaining the non-spin axes rates equal to zero. Maintaining the non-spin axes rates at zero will force the spin vector to be along the spacecraft Z axis and maintain the gravity vector normal to the floor of the crew compartment. If we consider a simplified rigid body spacecraft model and only rate feedback, as shown in Figure 8.13 with a linearized model of the control moment gyro, the response p and q may be determined analytically; equivalently, the time constant of the system may be determined as a function of the gains K_p and K_q and the CMG angular momentum H. The time constant of the system is the time required for the system to damp to 37% of its initial value. We can establish the best values of gain and CMG size by choosing values which minimize the time constant. Results for Moby Dick configuration MD-3 are given in Figure 8.14 for a CMG of 1,000 ft-lb-sec and for the CCV when considered as a rigid body. The 1,000 or 2,000 ft-lb-sec gyro is acceptable for either vehicle. The range of gains which should be used for the Moby Dick is from 2 to 20. The minimum of the curve occurs at 5, as seen in Figure 8.14. Similar results for the CCV considered as a rigid body indicate that the rate gain of the CCV should be in the order of 25.

8.3.4.3 Cable Connected Vehicle (CCV) Simulation

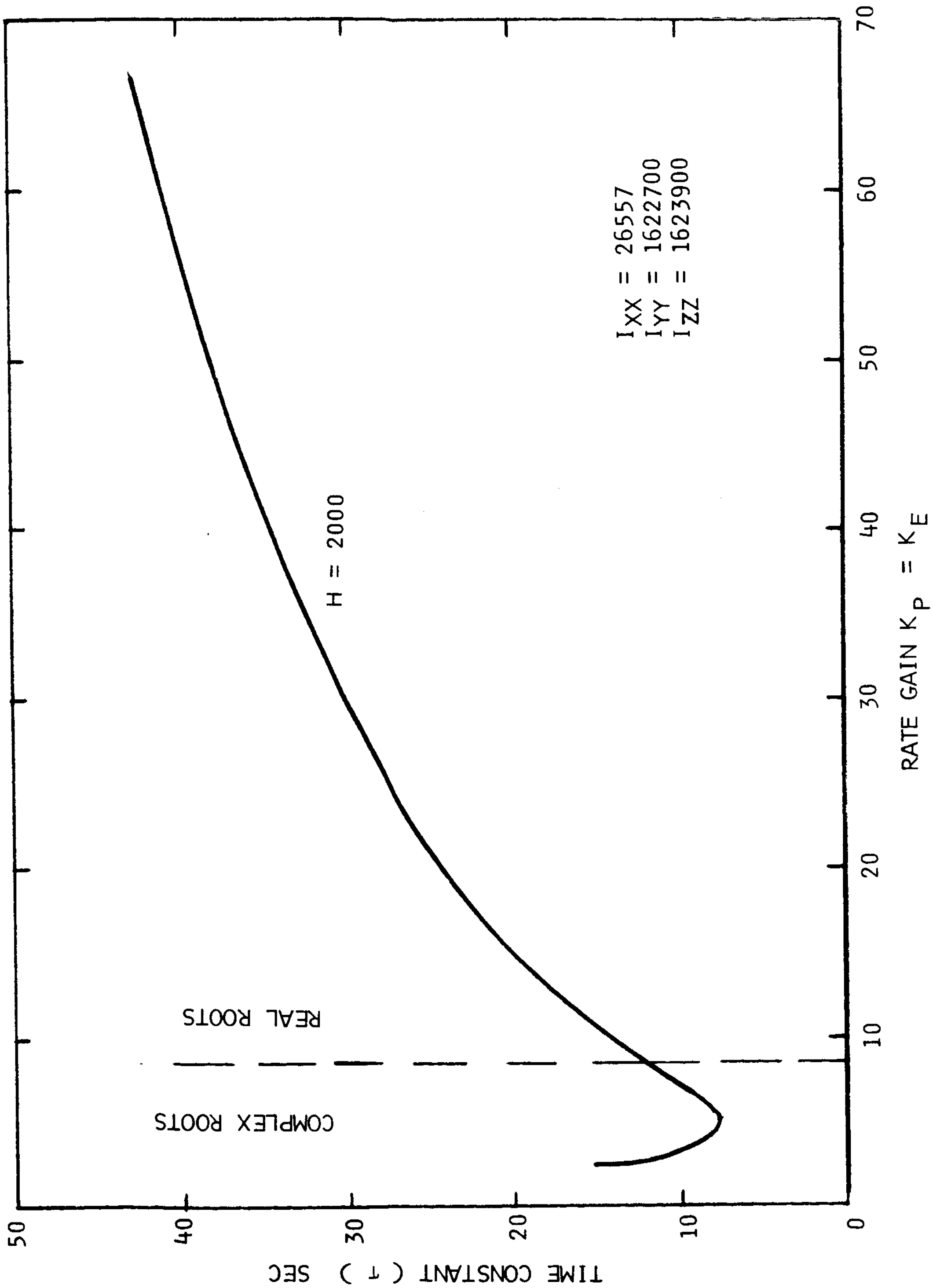
A digital simulation of the dynamics of the CCV has been conducted to establish the feasibility of controlling this vehicle. The simulation included six degrees of freedom for each of the two bodies with constraint equations for the connecting cable. A preliminary control system using on-off RCS control with a proportional CMG controller was simulated. The primary problem seemed to be the spin-up dynamics which will be discussed first.

Spin-up technique has been discussed in Section 8.3.1.2. It was found that the vehicles should be spun up to a rate $\Omega \pm$



LINEARIZED CONTROL SCHEMATIC

FIGURE 8.13



MD TIME CONSTANT VRS RATE GAIN

FIGURE 8.14

and the cable deployed while this rate was held constant. To minimize the propellant required, $\Omega^{\pm}$ should be as small as possible. However, some minimum value is necessary to prevent excessive attitude excursions of the CSM with respect to the cable. A value which has been tried and found satisfactory is .05 rad/sec. A procedure which was found to yield satisfactory response is to fire two thrusters parallel to the Z axis and one minus X thruster as indicated in Figure 8.15. The minus X thruster is required to obtain the proper torque-to-inertia ratio on body one compared to the torque-to-inertia ratio of the total system. Ideally, these two should be equal, but for two Z axis jets, the torque-to-inertia ratio of body one is considerably higher than the total; therefore, the minus X axis jet is required.

A short time response of the vehicle in the spin plane in terms of the variable ψ_{S1} is shown in Figure 8.16. The critical phase for spin-up after deployment is shown. Note that the maximum angle ψ_{S1} is 1.75 degrees. The response for subsequent spin-up maneuvers would be less than this value.

The response of the vehicle in the non-spin axes has been simulated with and without the CMG controller in the X and Z axes. The controlled response to a disturbance due to crew motion in the Y axis is shown in Figure 8.17. The variable is the angle of the CSM X axis with respect to the cable for oscillation about the Z axis. This is the comparable angle Θ_{S1} to ψ_{S1} shown in Figure 8.15 in the X-Y plane.

8.3.4.4 Passive Damper Analysis

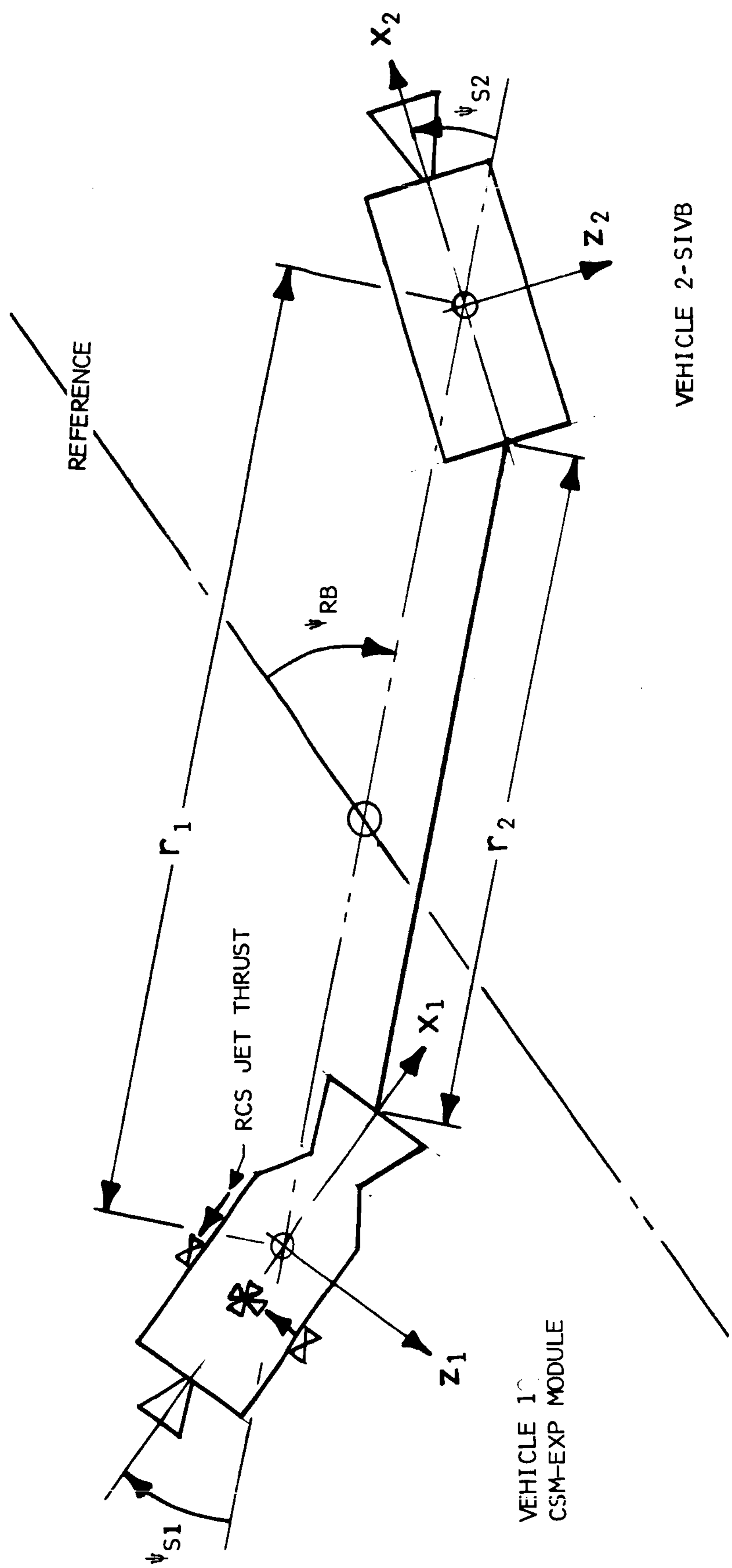
Since the artificial gravity vehicle will be limited in RCS propellant and power for the CMG's, passive damping techniques are considered. Three types of passive dampers are considered:

1. Modification of the engine bell servos of the S-IVB to act as dampers, so that the S-IVB engine bell would become a damping pendulum (Fig. 8.18).

2. Attaching damping pendulums to the S-IVB (Fig. 8.19).

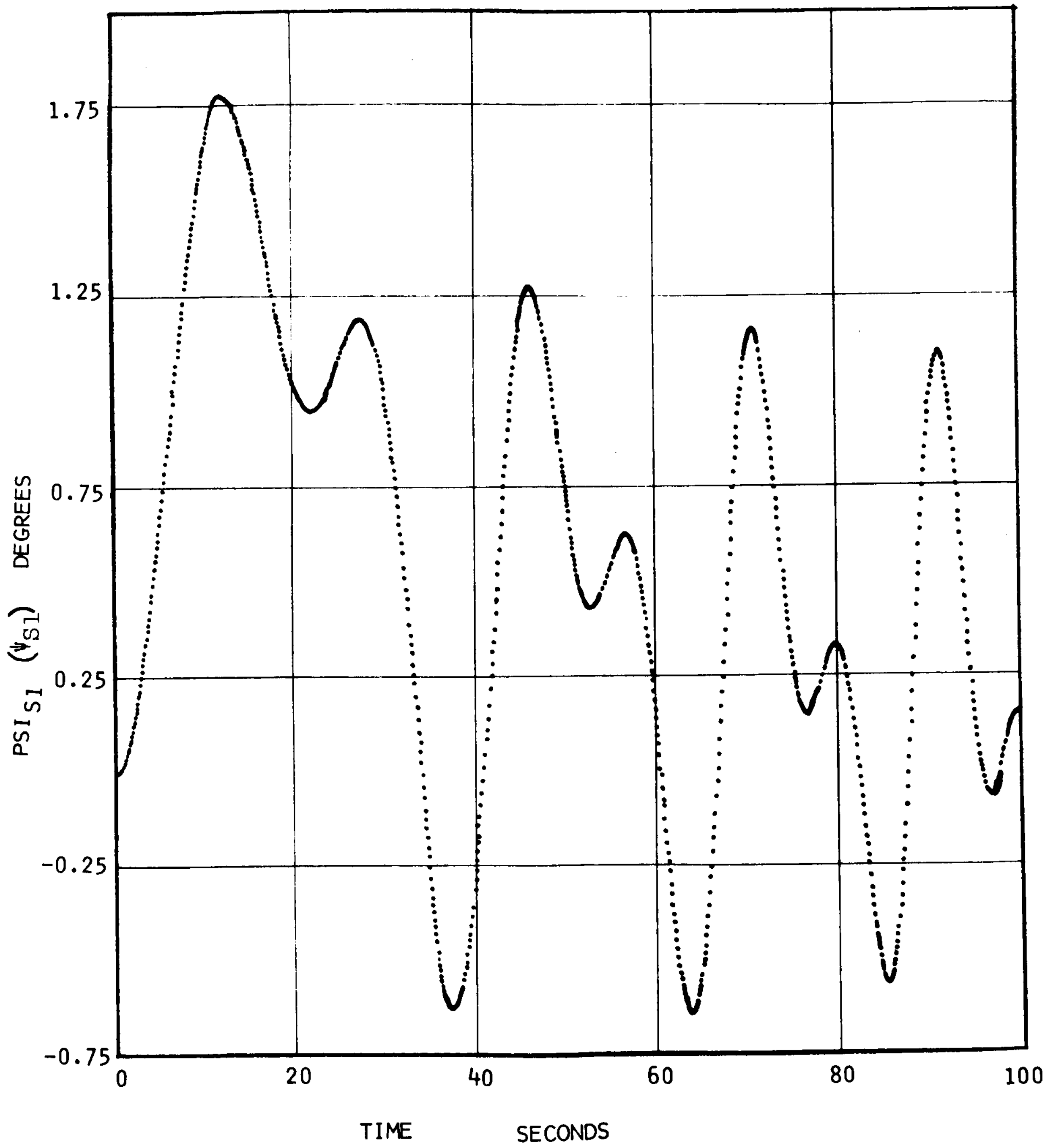
3. Coupling the Apollo CSM and experiment module to the cable reel with shock absorbers (Fig. 7.13).

In each case, the vehicle whose motion is to be damped (S-IVB or CSM & Experiment Module) was considered to be a pendulum in a centrifugal field, suspended at its point of attachment to the connecting cable. It is fully realized that settling times derived from this assumption are very



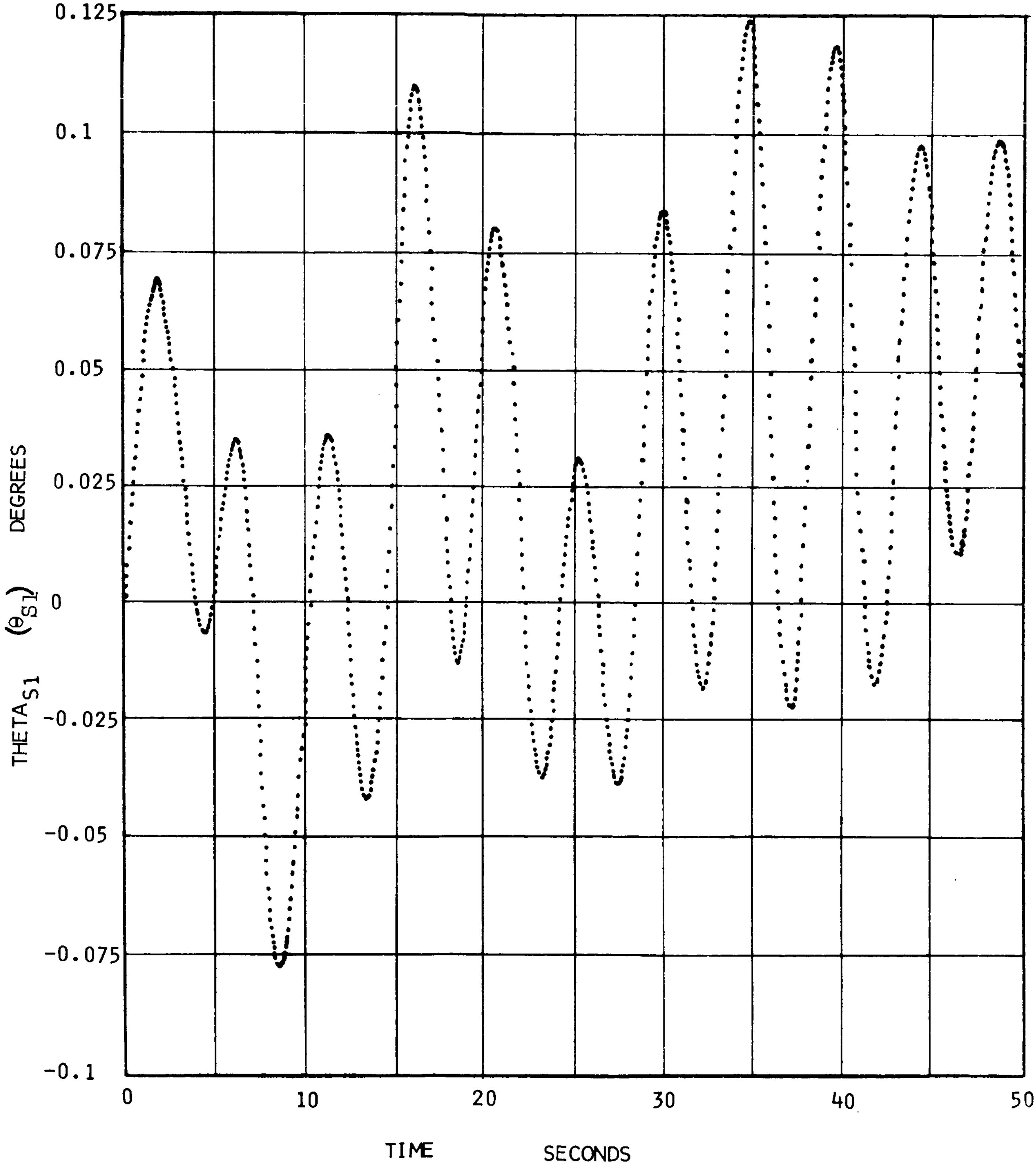
SPIN PLANE GEOMETRY

FIGURE 8.15



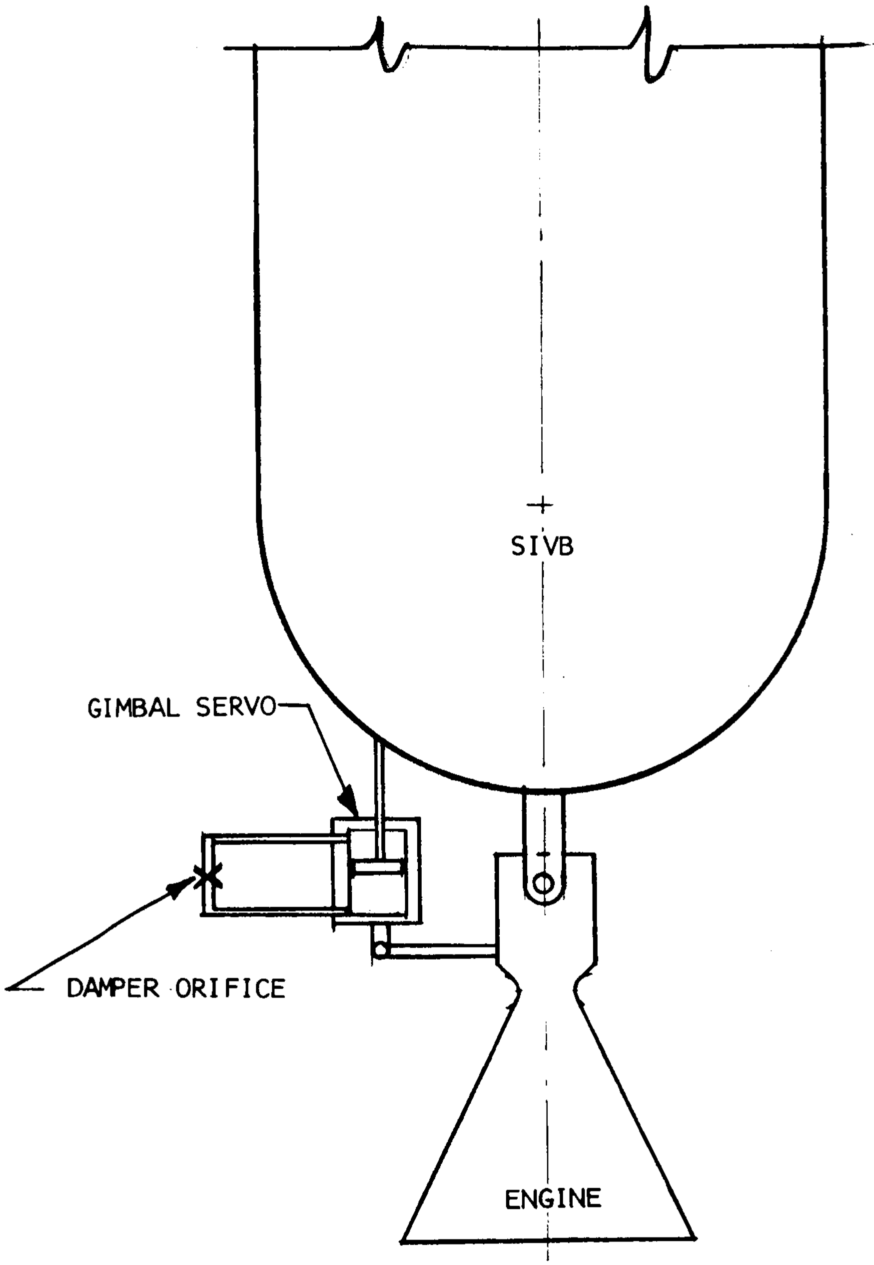
VEHICLE RESPONSE TO SPIN-UP

FIGURE 8.16



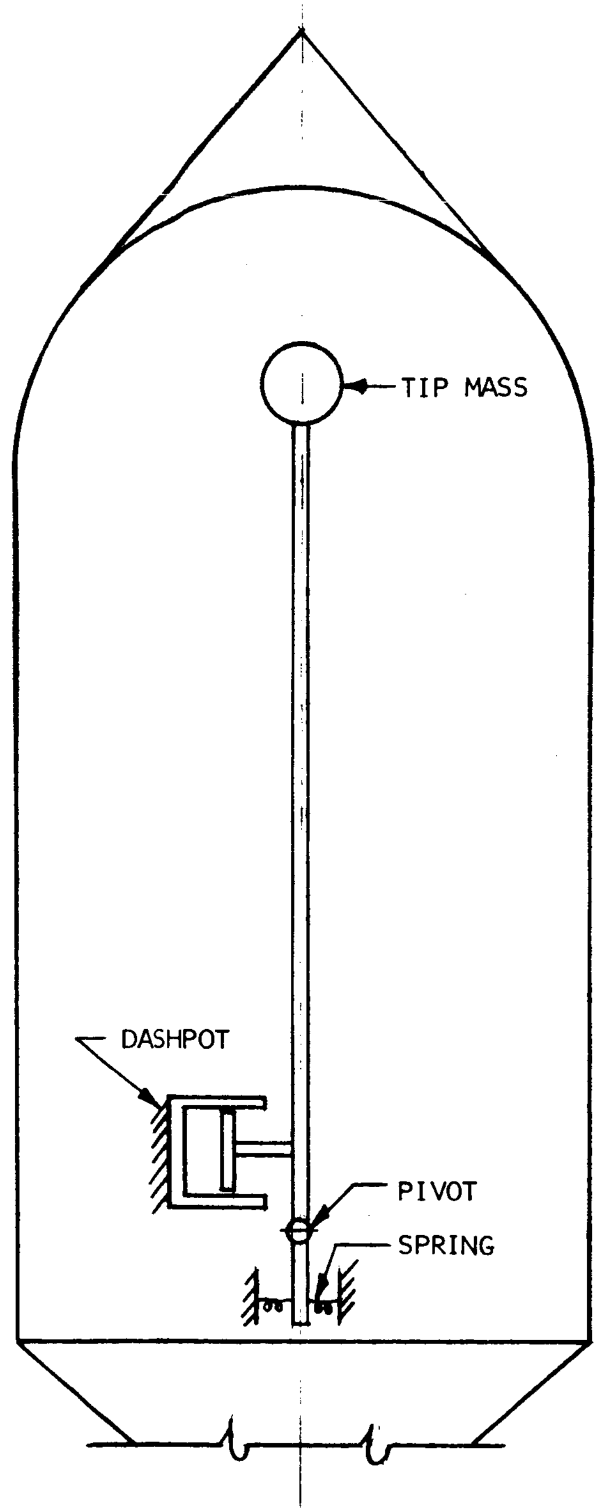
VEHICLE RESPONSE TO CREW MOTION

FIGURE 8.17



MODIFICATION OF GIMBAL SERVO
TO DAMPER
SCHEMATIC

FIGURE 8.18



DAMPING PENDULUM ON S-IVB
SCHEMATIC

FIGURE 8.19

optimistic, since only one mode of oscillation is considered and the effects of energy exchanges between the two vehicles via cable oscillations are entirely neglected. Analyses of the first two damping modes suggested are presented in detail in paragraphs 8.3.4.4.1 and 8.3.4.4.2.

The results of this analysis may be summarized as follows:

1. Optimum damping using the S-IVB engine as a damper will result from coupling the engine to the S-IVB with a viscous coupling of 357 ft-lb/rad/sec. This results in a time-to-damp to 1/e of the initial amplitude of about 2,000 sec., or about 100 minutes to damp to 5%.

2. If a damping pendulum is set with the pivot at the far end with the pendulum boom having an equilibrium position parallel to the X axis of the S-IVB, tip mass of 6 slugs, and length equal to the S-IVB, a spring constant of 3,190 ft-lb/rad and a damping constant of 5,700 ft-lb/rad/sec will give a settling time of about 10 minutes.

3. Treating the CSM and Experiment Module as a simple pendulum suspended from the swivel, its moment of inertia is 366,000 slug-ft^2 about the point of suspension, mass 992 slugs, and distance from the swivel to the cg is 16 2/3 ft. It can be shown that in a 0.3 g field, a damping constant of 462,000 ft-lb/rad/sec is required for critical damping. This gives a theoretical settling time of about 5 seconds. The stiffness of the linear shock absorbers required to furnish this damping factor is inversely proportional to the square of the distance from the swivel to the axis of the shock absorber. In the configuration shown in Figure 7.13, each shock absorber would have a stiffness of 231,000 lb/ft/sec if t if the distance from it to the swivel is one foot.

It appears probable, from these considerations, that a properly designed shock absorber coupling would provide the most rapid dissipation of undesired oscillations and be most economical from the viewpoint of weight.

8.3.4.4.1 S-IVB Gimballed Engine as a Damping Pendulum

One possible damping technique would be to use the S-IVB engine and its actuators as a damper. By the addition of suitable valves and tubing, the hydraulic actuators could be converted to viscous dampers. In addition, small masses at the ends of long booms could be deployed in the spin plane to inhibit roll.

For preliminary design purposes, a mathematical model will be derived considering the Saturn IVB and its engine as a compound pendulum suspended in a centrifugal field. It is realized that this is a highly over-simplified model. However, it is subject to linear analysis, and will supply useful "ball park" design parameters. Any final design must be based upon a computer study. For this model, small angle approximations will be made and Coriolis forces will be neglected.

The approximate equations of motion of the vehicle plus engine are:

$$I_r \ddot{\Theta}_r = -m_r\, x_r\, (r+r_v)\, \omega^2\, \Theta_V - c\,(\dot{\Theta}_V - \dot{\Theta}_E) - m_E\,(r+l)\omega^2\Theta_V \qquad (1)$$

$$I_E \ddot{\Theta}_E = c(\dot{\Theta}_V - \dot{\Theta}_E) - m_E\, x_E\, (1+x_E)\, \Theta_E\, \omega^2 \qquad (2)$$

where:

X_E - distance of engine cg to gimbal (about one ft)

I_V - moment of inertia of vehicle about cable end (2,079,000 sl-ft^2)

I_E - moment of inertia of engine about gimbal (220 sl-ft^2)

m_V - mass of vehicle (1,263 slugs)

X_V - distance of Saturn IVB cg from cable end (23 ft)

l - length of Saturn IVB from cable end to engine gimbal (44 ft)

ω - rate of rotation of vehicle (.4 rad/sec)

C - viscous coupling constant (ft-lbs/rad/sec)

Θ_V - angle between engine center-line and cable

Θ_E - angle between engine center-line and cable

r - length of cable from center of rotation to attachment to Saturn IVB (75 ft)

The major effort in design is to determine what value of C will give the minimum settling time for the S-IVB and engine configuration. This C can be achieved by bypass tubes between the ends of the hydraulic actuator cylinders with suitable orifices.

Substituting the above values and Laplace transforming the above equations (1) and (2),

$$\begin{bmatrix} 2.1 \times 10^6 s^2 + C_s + 4.8 \times 10^5 & -C_s \\ -C_s & 220 + C_s + 144 \end{bmatrix} \begin{bmatrix} \Theta_V \\ \Theta_E \end{bmatrix} = 0 \qquad (3)$$

Therefore, the characteristic equation of the system is:

$$4.68 \times 10^8 S^4 + 2.1 \times 10^6 C S^3 + 4.08 \times 10^8 S^2 + 4.8 \times 10^5 CS + 6.91 \times 10^7 = 0 \qquad (4)$$

or:

$$\frac{C_s (S^2 + .2287)}{223 (S^4 + .872S^2 + .1477)} = \frac{C_s (S^2 + .228)}{223 (S^2 + .2300)(S^2 + .042)} = -1 \qquad (4)$$

which is recognizable as one of the forms suitable for root-locus studies. Since the two imaginary zeros practically cancel two of the poles, the shape thereof is a semicircle in the left half-plane terminating at $\pm.8j$ plus the negative real axis (Fig. 8.20).

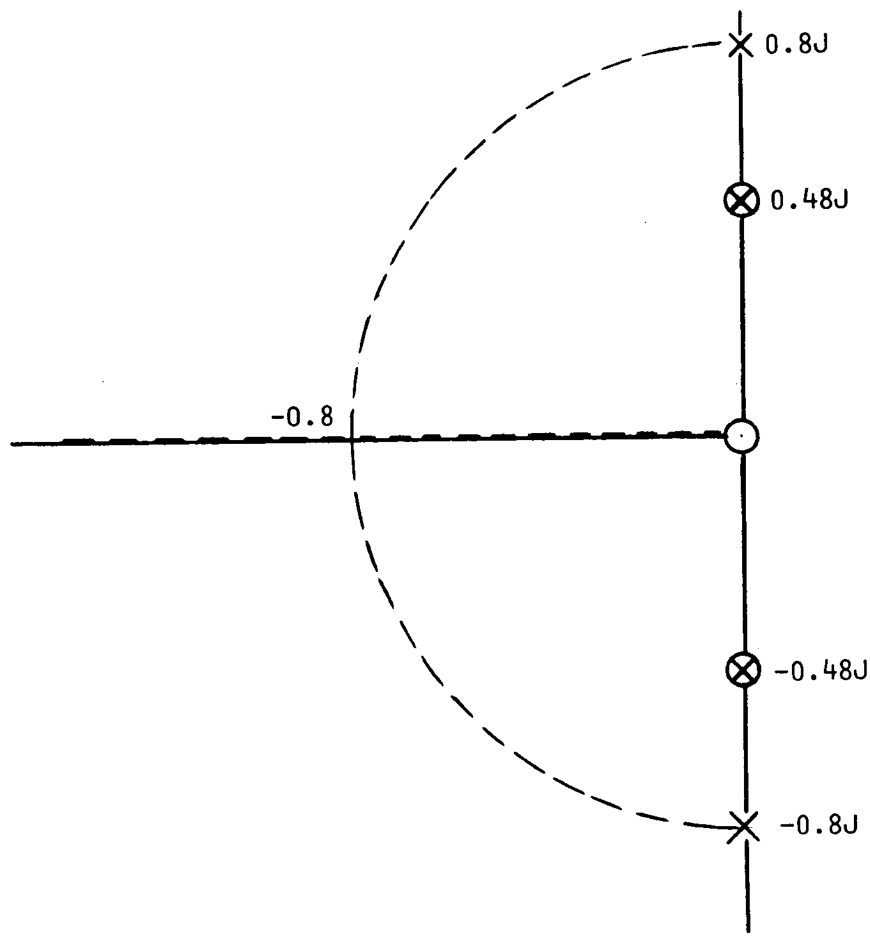
To adjust the system to be essentially critically damped, an operating point of S = -.8 is chosen, giving C = 357 ft-lb per rad/sec. This gives the factors of the characteristic equation (4) as $S^2 + 1.65 + .64$ and $S^2 + .001_S + .2287$. The damping factor (S) of the first is 1.0 (as chosen) and natural frequency (W_n) .8; of the second, S = .001 and $W_n = 0.478$. Therefore, the settling time of the second mode is that of the system.

The time constant, or time to damp to 37 percent of initial amplitude, is 2,000 sec.

It may be possible to improve the performance of the damping system further by making the damping coefficient a function of $(\dot{\Theta}_E - \dot{\Theta}_V)$. This could be accomplished by using a spring-loaded pintle with required contour in the orifice in the damper tube.

8.3.4.4.2 General Considerations of Damping Pendulum Design

Another possible approach to be considered is to design a damping pendulum to be placed on the S-IVB to damp out oscillations and to alter the moment of inertia distribution so that it will spin about the nominal spin axis with minimal tendency to roll. However, if the rest axes of these pendulums are perpendicular to the roll axis of the vehicle, "centrifugal force" cannot be used as the restoring force



ROOT LOCUS OF EQUATION

S-IVB AND ENGINE WITH VISCOUS COUPLING

FIGURE 8.20

and a spring must maintain them in the desired orientation. The addition of such a spring will provide another mode of energy storage and thus decrease the effective damping. Therefore, these pendulums should be deployed so that they may swing about an equilibrium position parallel to the S-IVB X-axis. From the same consideration of energy storage minimization, it may be recommended that the cg of the damping pendulums be as close to the pivot as possible.

It will be helpful to attempt to derive some generalized design criteria for damping pendulums. The general equations of motion for mechanically coupled pendulums are:

$$I_1 \ddot{\Theta}_1 + C(\dot{\Theta}_1 - \dot{\Theta}_2) + K_1\Theta_1 + K_m(\Theta_1 - \Theta_2) = 0 \qquad (5)$$

$$I_2 \ddot{\Theta}_2 + C(\dot{\Theta}_2 - \dot{\Theta}_1) + K_2\Theta_2 + K_m(\Theta_2 - \Theta_1) = 0 \qquad (6)$$

where K_1 and K_2 are the individual environmental "spring constants" and K_m the constant of the coupling spring.

After Laplace transforming, the characteristic equation of the system may be shown to be:

$$I_1 I_2 S^4 + C(I_1+I_2)S^3 + \left[(K_1+K_m)I_2 + (K_2+K_m)I_1\right] S^2 \qquad (7)$$

$$+ C(K_1+K_2)S + K_1K_2 + K_m(K_1+K_2) = 0$$

and the poles and zeros of the root-locus with variable C may be obtained from

$$\frac{C\left[(I_1+I_2)S^2 + K_1 + K_2\right]S}{I_1 I_2 S^4 + \left[K_1 I_2 + K_2 I_1 + K_m(I_1+I_2)\right]S^2 + K_1K_2 + K_m(K_1+K_2)} = -1 \qquad (8)$$

the zeros being:

$$0, \pm j\sqrt{\frac{K_1+K_2}{I_1+I_2}}$$

and the poles being the negatives of the denominator roots.

If $K_m \equiv 0$, that is, the coupling is purely viscous, the poles are at:

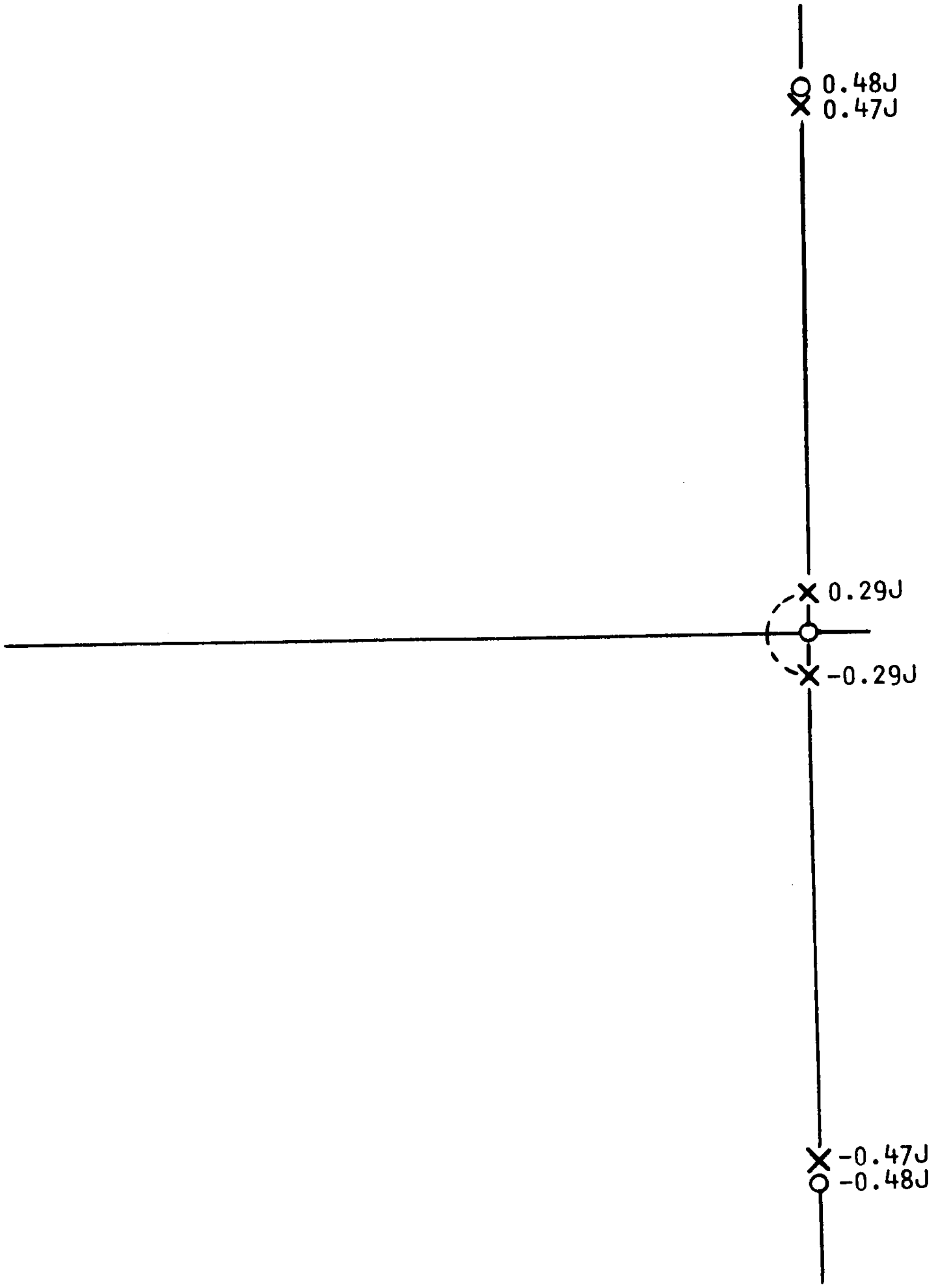
$$\pm j\sqrt{\frac{K_1}{I_1}} \quad \text{and} \quad \pm j\sqrt{\frac{K_2}{I_2}}$$

If we take K_1 and I_1 as the characteristics of the S-IVB, they are fixed at 480,000 ft-lb/rad and 2.1 x 10^6 slug-ft^2, respectively, giving poles at $\pm$ .478. For a simple pendulum, $K_2 = m(1 = r)lw^2$ and $I_2 = ml^2$. Therefore, the position of the poles due to this pendulum is $\pm j\, w(1 + r/l)^{\frac{1}{2}}$.

Since some separation of the imaginary zeros from both the vehicle and pendulum poles is desired for allowing choice of an optimum value of C, the position of the zeros must be regulated by the choice of the value of K_2. For a tip mass of 6 slugs (200 lbs) this would require a pendulum length of 650 ft and the resulting I_2 would be 2.54 x 10^6 sl-ft^2. Since the ratio of I_2 and K_2 is quite close to that of I_1 and K_1, the zero would remain essentially in the same place. It is to be expected, from physical considerations, that the portion of the root-locus originating at the well-separated poles and zero describes the dynamics of the angle between the pendulum and the vehicle (Θ_1 and Θ_2), and the portions between the almost cancelling poles and zeros the behavior of the individual angles.

Because of the difficulty of separating the poles and zeros of an aft-pointing pendulum, let us consider a forward pointing one. In this case, the environmental "spring constant" is negative and equal to $-m(r-l)lw^2$. For the pendulum to be completely stable, and not swing into the aft position, a spring coupling with a K_m of at least 2 mrl w^2/π must be provided. Assuming a 6 slug end mass, a pivot at the aft end of the S-IVB and a boom length of the length of the S-IVB gives an I_2 of 11,600 sl-ft^2, a K_1 of -3170, and a K_2 of 3,190 ft/lb/rad. This results in the zeros of equation (8) being at 0 and $\pm$ .48j and the poles at $\pm$ .029j and $\pm$ .47j. The resulting root-locus is shown in Figure 8.21.

A C of 5,700 ft-lb/rad/sec will result in a minimum settling time of the oscillatory mode, with a damping factor of 0.01 and frequency of .47. It is doubted that higher damping factors can be achieved for relatively low damping pendulum masses. In addition, two exponential decays with time constants of 60 seconds and 2 seconds are also present in the response. The settling time for the system is of the order of 600 seconds or 10 minutes.



ROOT LOCUS OF EQUATION OF
SUGGESTED DAMPING PENDULUM

FIGURE 8.21

8.4 Conclusion

The control of the CCV as well as the MD appears feasible. The control system may be configured from developed components such as the AAP CMG system. The CCV offers some advantages over the MD from the G&C point of view; however, the control design will be more complicated. Reliance should be placed on MOL experience as well as AAP as similar type functions are planned for these programs. A preliminary system has been presented in Section 8.3.2.

9.0 CONCEPTS

The three artificial gravity concepts shown on Figure 9.1 were investigated during the course of this study. Each was developed in sufficient depth to permit comparison in the areas of physical properties, operational characteristics and general technology advancement.

Since the program would be conducted by the AAP Office, their cluster concept was considered the starting point and the available data were utilized in the final concept comparison.

A short investigation of the Moby Dick concept had been completed by the Advanced Spacecraft Technology Division prior to the beginning of the artificial gravity study. These data and drawings were available and were subsequently integrated into this study. Further configuration design was indicated and, when completed, permitted this concept to be compared on an equal basis with the other two.

The cable-connected vehicle-type of space station has been studied in the past by industry. Apparently, although it possesses some rather attractive features, no station designs have been completed. Because of this, the problem areas (primarily stabilization and control of the station and the method of extending the counterweight) were investigated in sufficient depth to permit reasonable configurations to be designed. Valid comparisons could then be made with the other two concepts.

9.1 Cluster

The Cluster concept shown on Figure 9.2 was devised by the AAP as a "built-up" station. It utilizes several components used during the AAP flights, thereby gaining an economical artificial gravity station. However, some inherent problems exist with this vehicle that probably eliminate it as a serious concept for further study.

First, the spin radius is approximately 30% shorter than that specified in the ground rules. To obtain the desired gravity level, the station would have to be rotated approximately 4.5 rpm. Since this is faster than the specified rotation speed, the station cannot meet the desired gravity levels within the specified constraints.

Second, the crew is separated by both distance and the spin axis. In the event of an emergency abort, too much time

ARTIFICIAL GRAVITY CONCEPTS

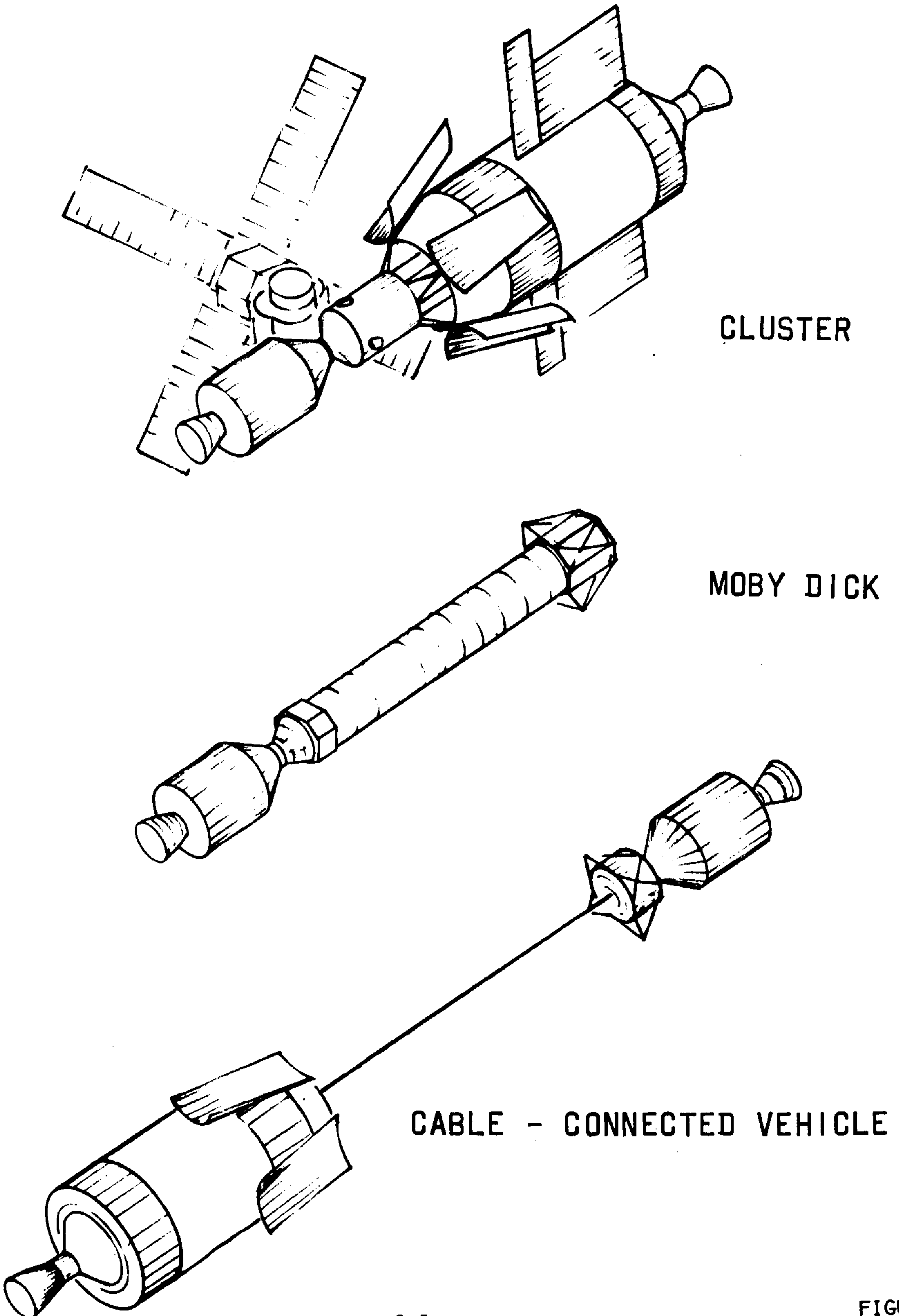
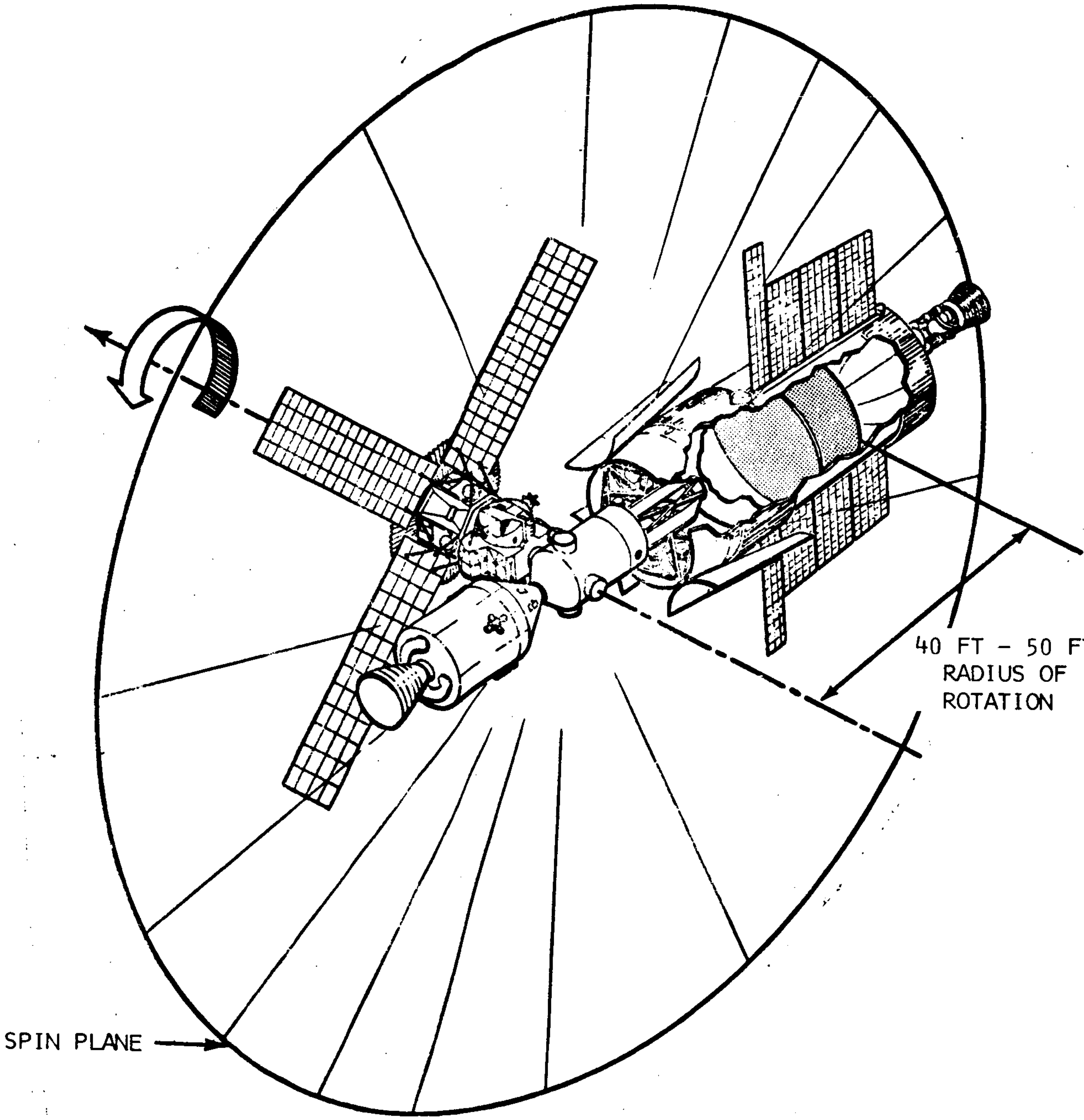


FIGURE 9.1



CLUSTER CONFIGURATION

FIGURE 9.2

would be used by the experiment crewmen getting from the Experiment Module to the Command Module. They would also have to cross the spin axis, which could be extremely difficult while the station is "spun-up".

Third, the Command Module crewman is on a very short spin radius, which would not give him any significant gravity level, but would magnify the Coriolis effects and stimulate the proprioceptive nerves, both vestibular and non-vestibular, far beyond the desired level. The man may, to the detriment of the mission, spend his entire 10 days struggling with nausea.

Fourth, the solar cell power system requires a specific orientation, with the spin plane normal to the Sun line. This places the Service Module in an intenable position, wherein half of the RCS and SPS tankage is superheated, while the other half is supercooled. However, this can be overcome by adding a heating unit on the "cold side".

Fifth, the stabilization during station operation will depend on the CMG mounted in the LM/ATM. Sensing devices in the S-IVB Workshop would have to be devised and their data fed to the CMG through long lines. Also, the CMG torque would have to be transmitted through the LM/ATM docking hatch, which may preclude precise stabilization adjustments of the overall system.

Sixth, the solar panels attached to the LM/ATM and the S-IVB Workshop would have to be designed to withstand the rotation rate of the artificial gravity concept.

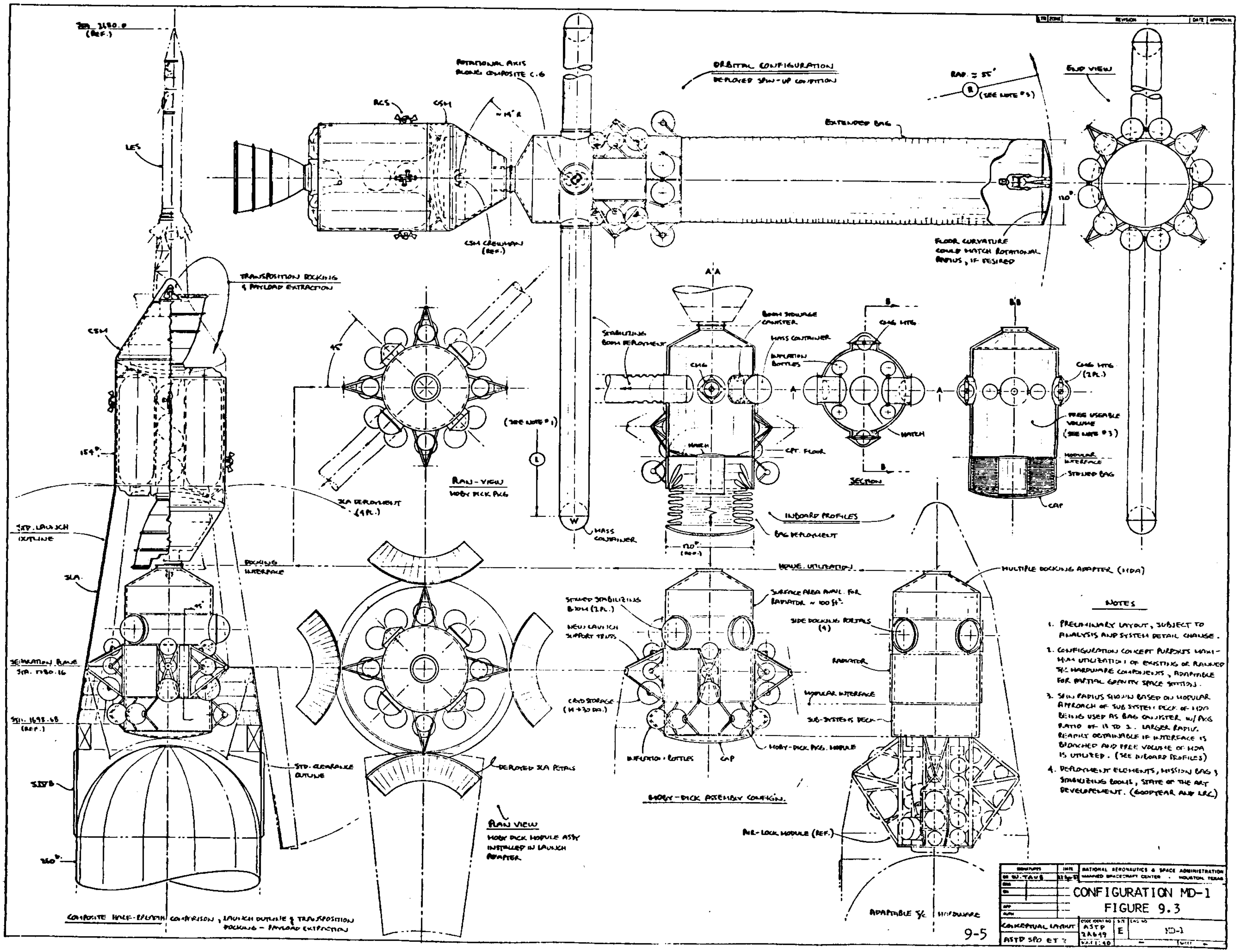
It was felt that because of these reasons, additional study of the Cluster was not justified.

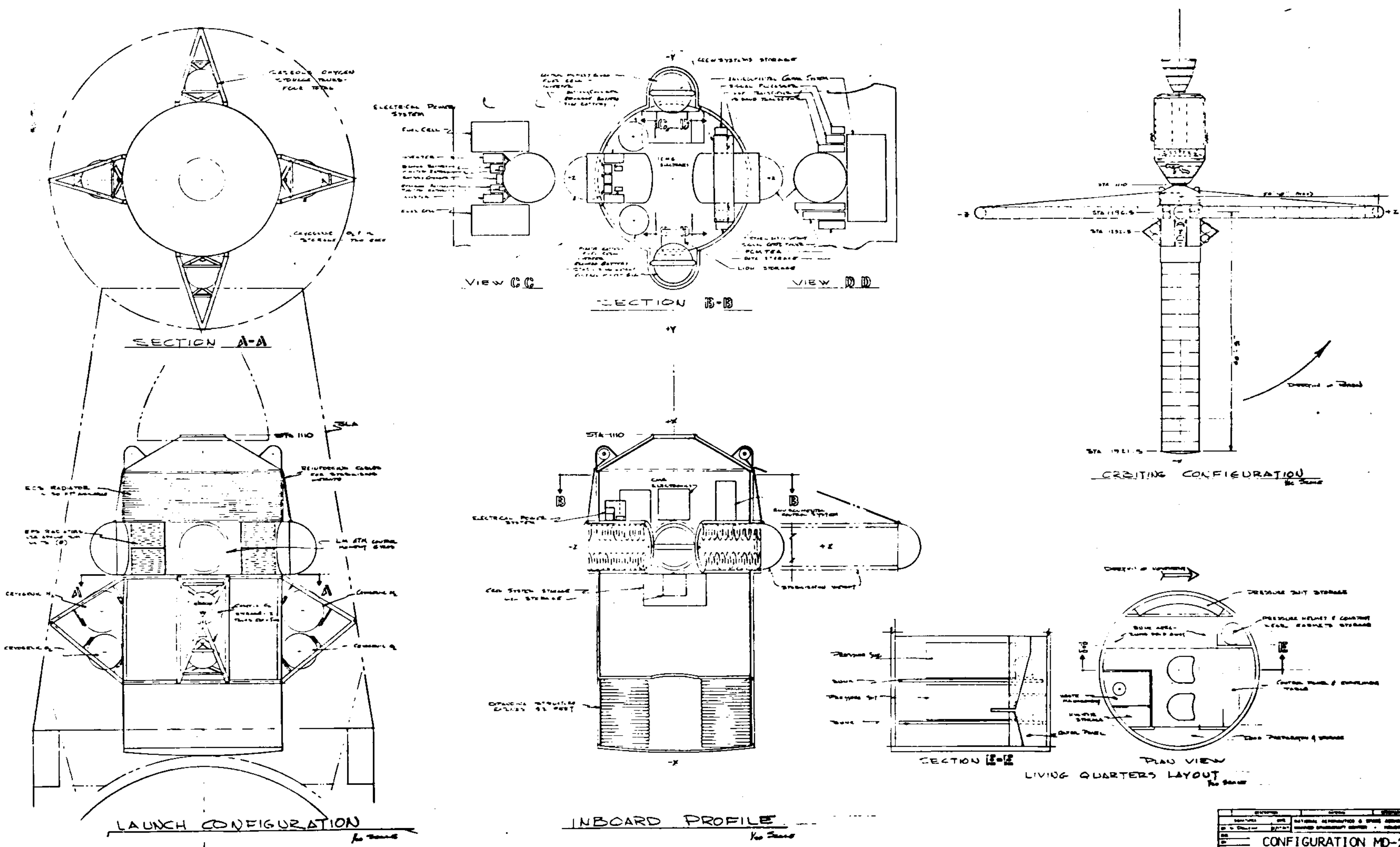
9.2 Moby Dick

The Moby Dick concept of using inflatable structure to provide a long, semi-rigid space station has been studied for some time. Theoretically, such a station should be easily stabilized and provide artificial gravity rather efficiently.

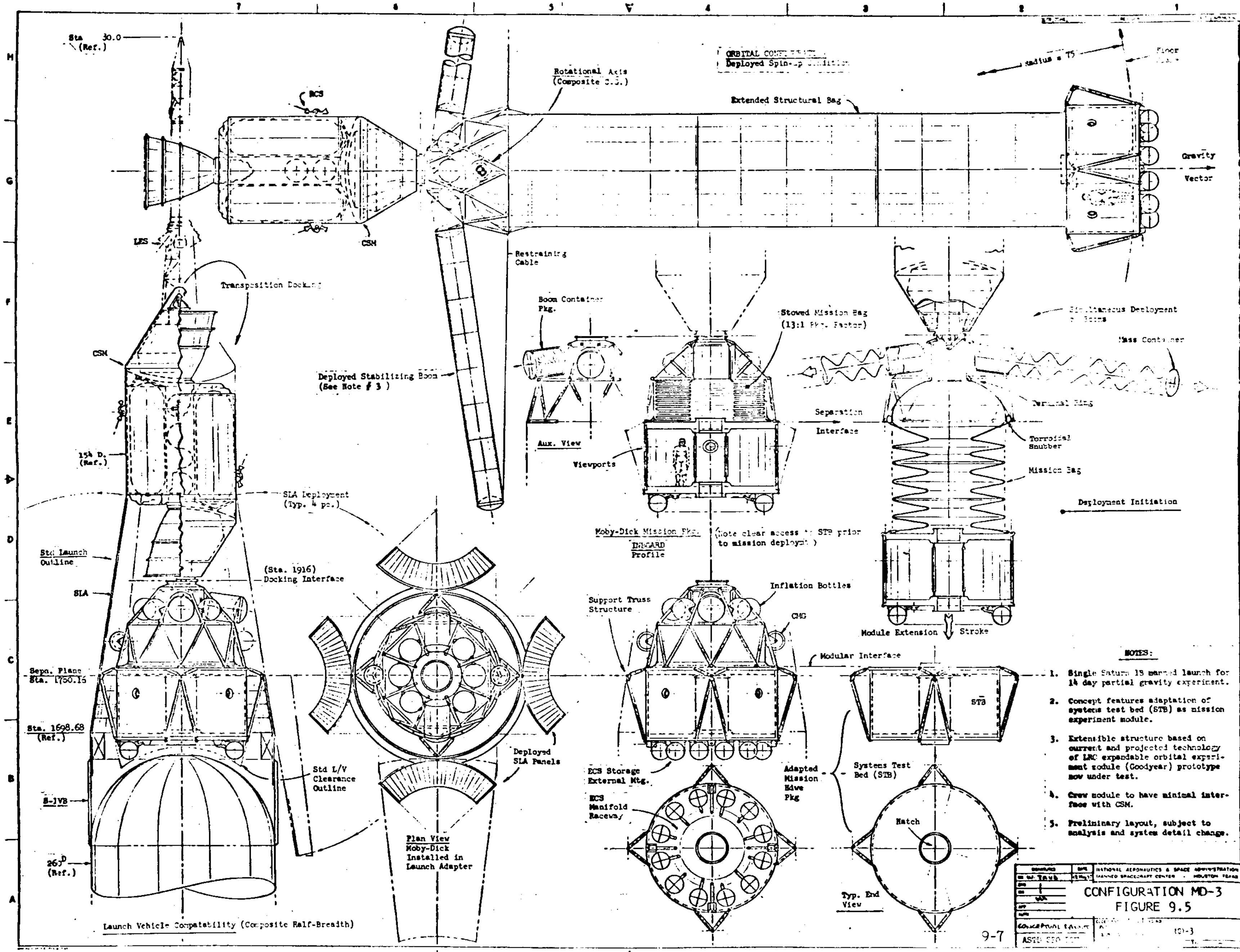
Accordingly, the artificial gravity study investigated this concept to determine just what could be accomplished with this type of structure. Six configurations were designed and compared on the basis of weight and complexity.

It was found that such a concept could indeed be developed to provide artificial gravity, within the guidelines for the study. The total weight left a pleasing margin for growth and the cost was not excessive.

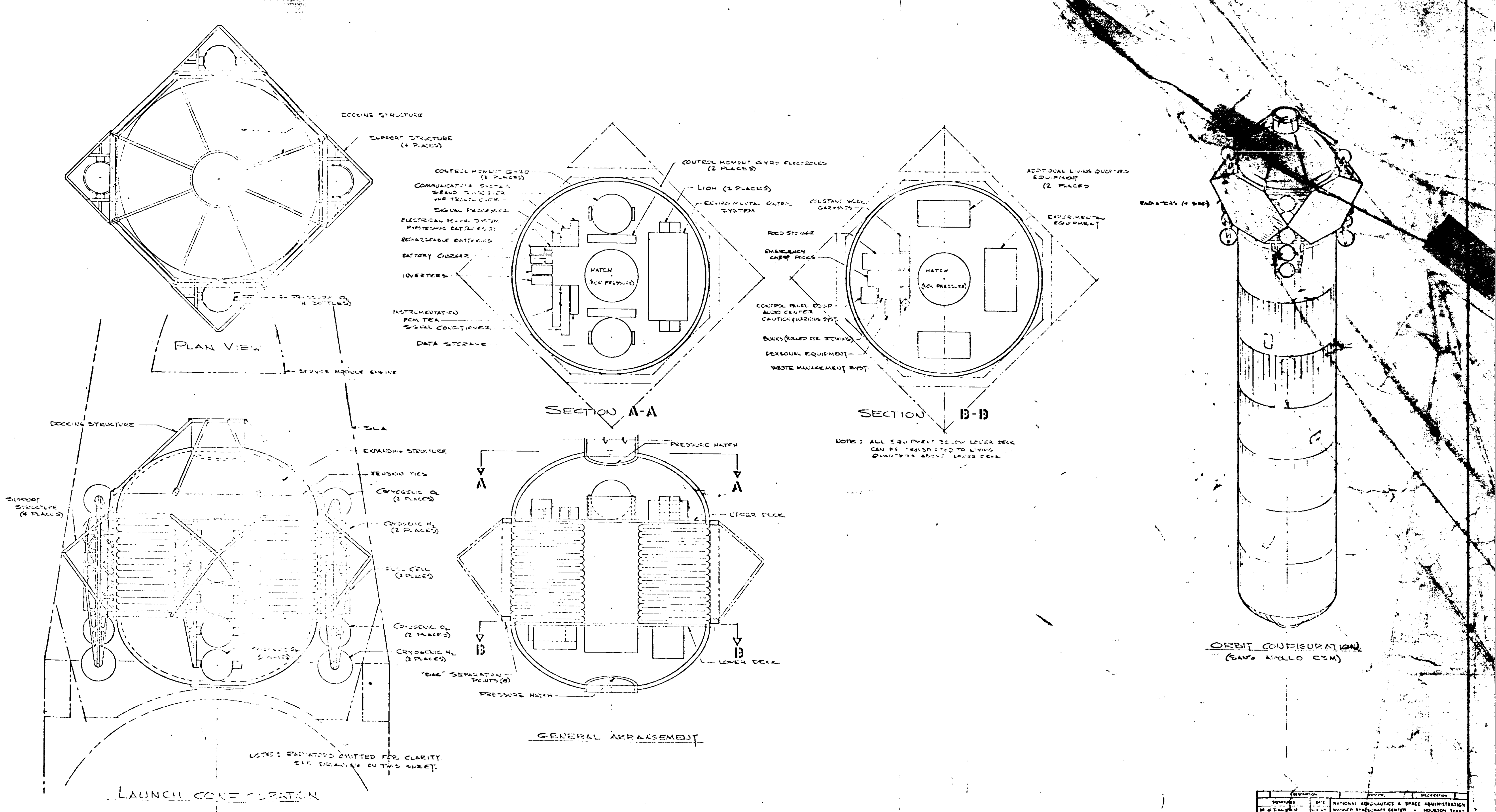

ORBITAL CONFIGURATION
DEPLOYED SPIN-UP CONDITION
ROTATIONAL AXIS
ALONG COMPOSITE C.G
RCS
CSM
CSM CREWMAN (REF.)
EXTENDED BAG
RAD. = 55'
(SEE NOTE #3)
END VIEW
FLOOR CURVATURE
COULD MATCH ROTATIONAL
RADIUS, IF DESIRED
LES
TRANSPOSITION DOCKING
& PAYLOAD EXTRACTION
STABILIZING
BOOM DEPLOYMENT
BOOM STOWAGE
CANISTER
MASS CONTAINER
INFLATION
BOTTLES
CMG
HATCH
CPT. FLOOR
CMG MTG.
(2 PL.)
FREE USEABLE
VOLUME
(SEE NOTE #3)
MODULAR
INTERFACE
STOWED BAG
CAP
SECTION
INBOARD PROFILES
BAG DEPLOYMENT
MASS
CONTAINER
(SEE NOTE #1)
PLAN-VIEW
MOBY DICK PKG
SLA DEPLOYMENT
(4 PL.)
STD. LAUNCH
OUTLINE
SLA
DOCKING
INTERFACE
MODULE UTILIZATION
MULTIPLE DOCKING ADAPTER (MDA)
STOWED STABILIZING
BOOM (2 PL.)
NEW LAUNCH
SUPPORT TRUSS
SURFACE AREA AVAIL. FOR
RADIATOR ≈ 100 ft².
SIDE DOCKING PORTALS
(4)
RADIATOR
MODULAR INTERFACE
SUB-SYSTEMS DECK
CRYO STORAGE
(H + 30 DA.)
MOBY-DICK PKG. MODULE
INFLATION BOTTLES
CAP
MOBY-DICK ASSEMBLY CONFIGN.
SEPARATION PLANE
STA. 1780.16
STA. 1698.68
(REF.)
SIVB
STD. CLEARANCE
OUTLINE
DEPLOYED SLA PETALS
PLAN VIEW
MOBY DICK MODULE ASSY
INSTALLED IN LAUNCH
ADAPTER
AIR-LOCK MODULE (REF.)
ADAPTABLE S/C HARDWARE
COMPOSITE HALF-SECTION COMPARISON, LAUNCH OUTLINE & TRANSPOSITION
DOCKING - PAYLOAD EXTRACTION
NOTES
1. PRELIMINARY LAYOUT, SUBJECT TO ANALYSIS AND SYSTEM DETAIL CHANGE.
2. CONFIGURATION CONCEPT PURPORTS MAXIMUM UTILIZATION OF EXISTING OR PLANNED S/C HARDWARE COMPONENTS, ADAPTABLE FOR PARTIAL GRAVITY SPACE STATIONS.
3. SPIN RADIUS SHOWN BASED ON MODULAR APPROACH OF SUB SYSTEM DECK OF MDA BEING USED AS BAG CANISTER W/ PKG RATIO OF 13 TO 1. LARGER RADIUS READILY OBTAINABLE IF INTERFACE IS BLOCKED AND FREE VOLUME OF MDA IS UTILIZED. (SEE INBOARD PROFILES)
4. DEPLOYMENT ELEMENTS, MISSION BAG & STABILIZING BOOMS, STATE OF THE ART DEVELOPEMENT. (GOODYEAR AND LRC)
NATIONAL AERONAUTICS & SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER · HOUSTON, TEXAS
CONCEPTUAL LAYOUT
ASTP SPO ET
CONFIGURATION MD-1
FIGURE 9.3



CONFIGURATION MD-2
FIGURE 9.4
MD-2



CONFIGURATION MD-3
FIGURE 9.5



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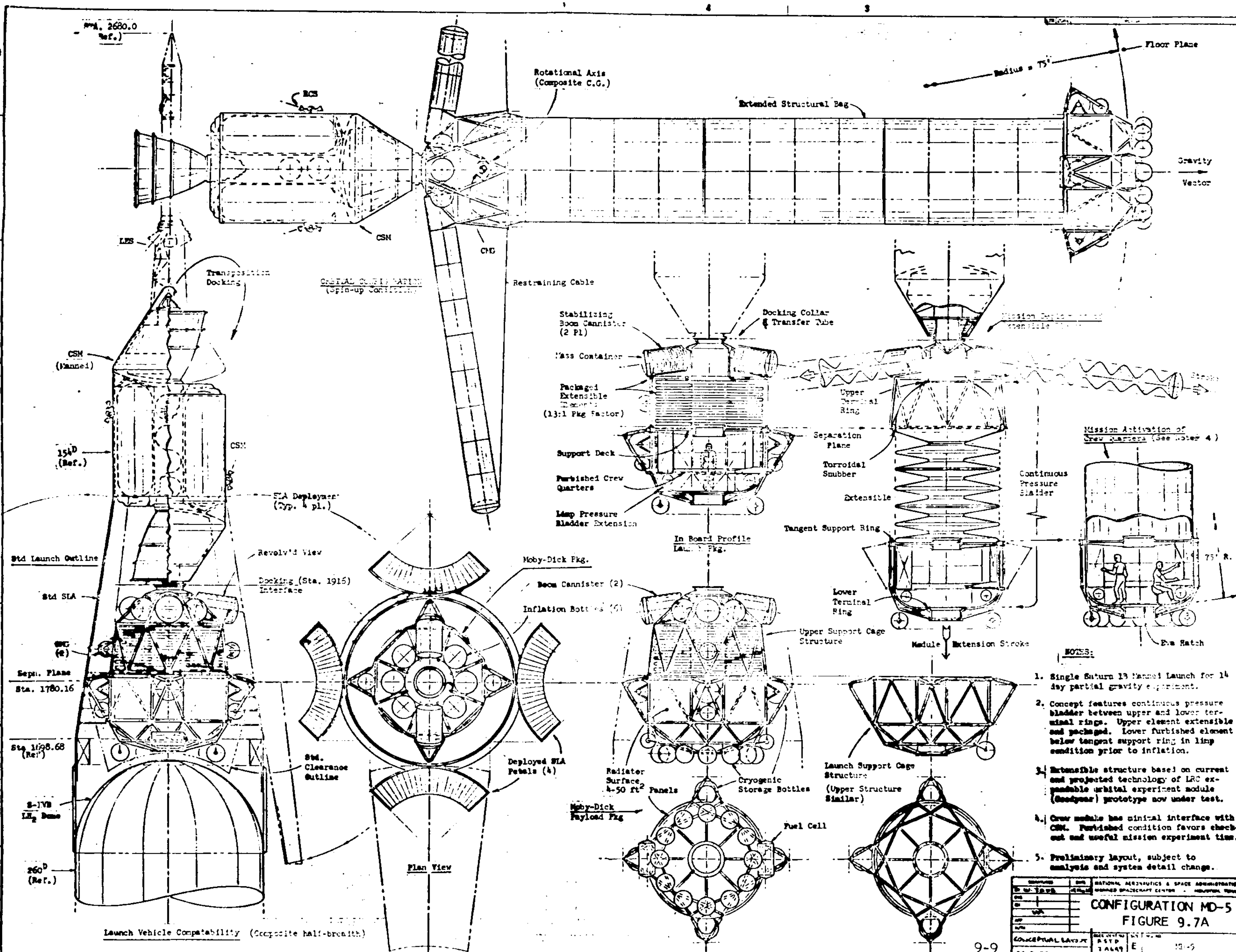
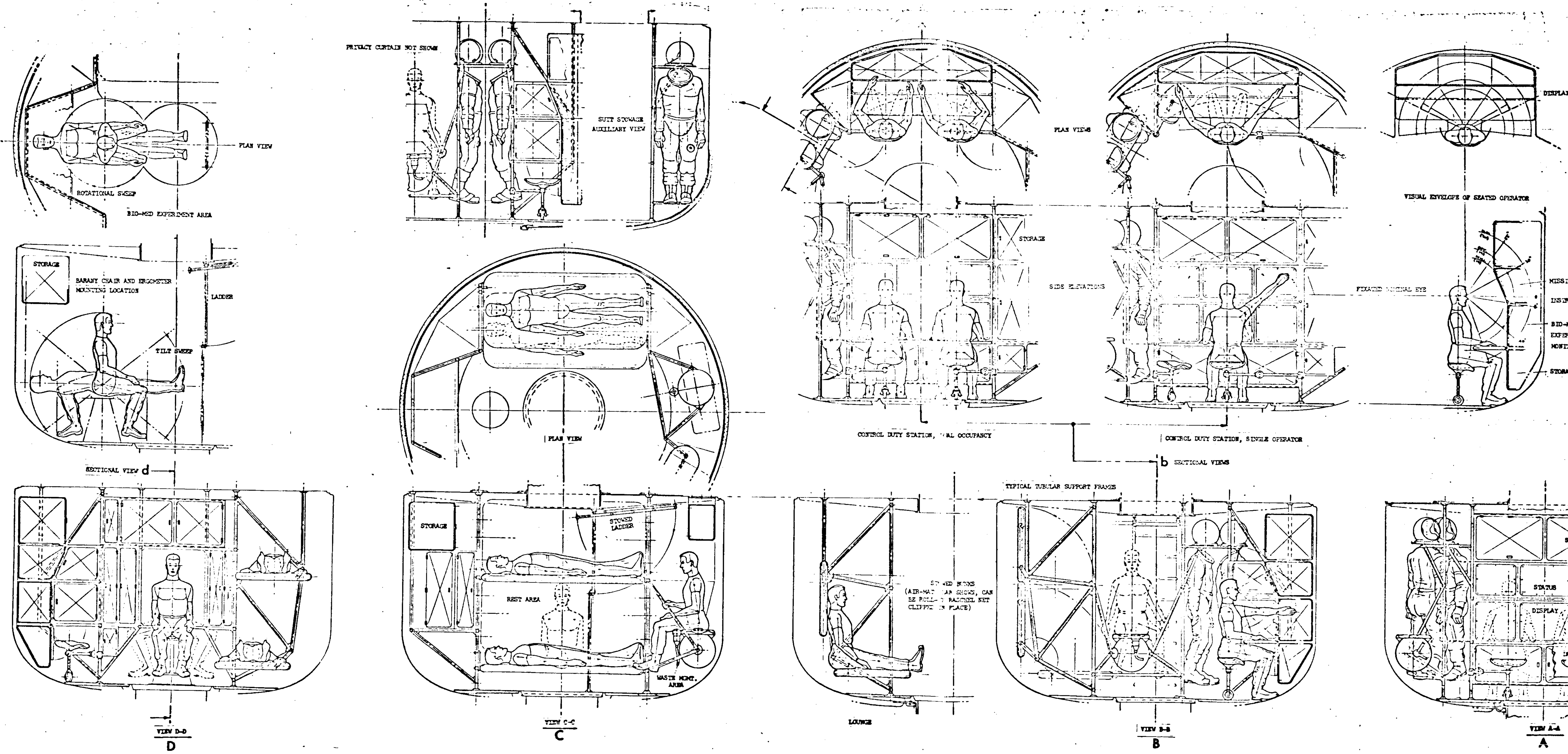
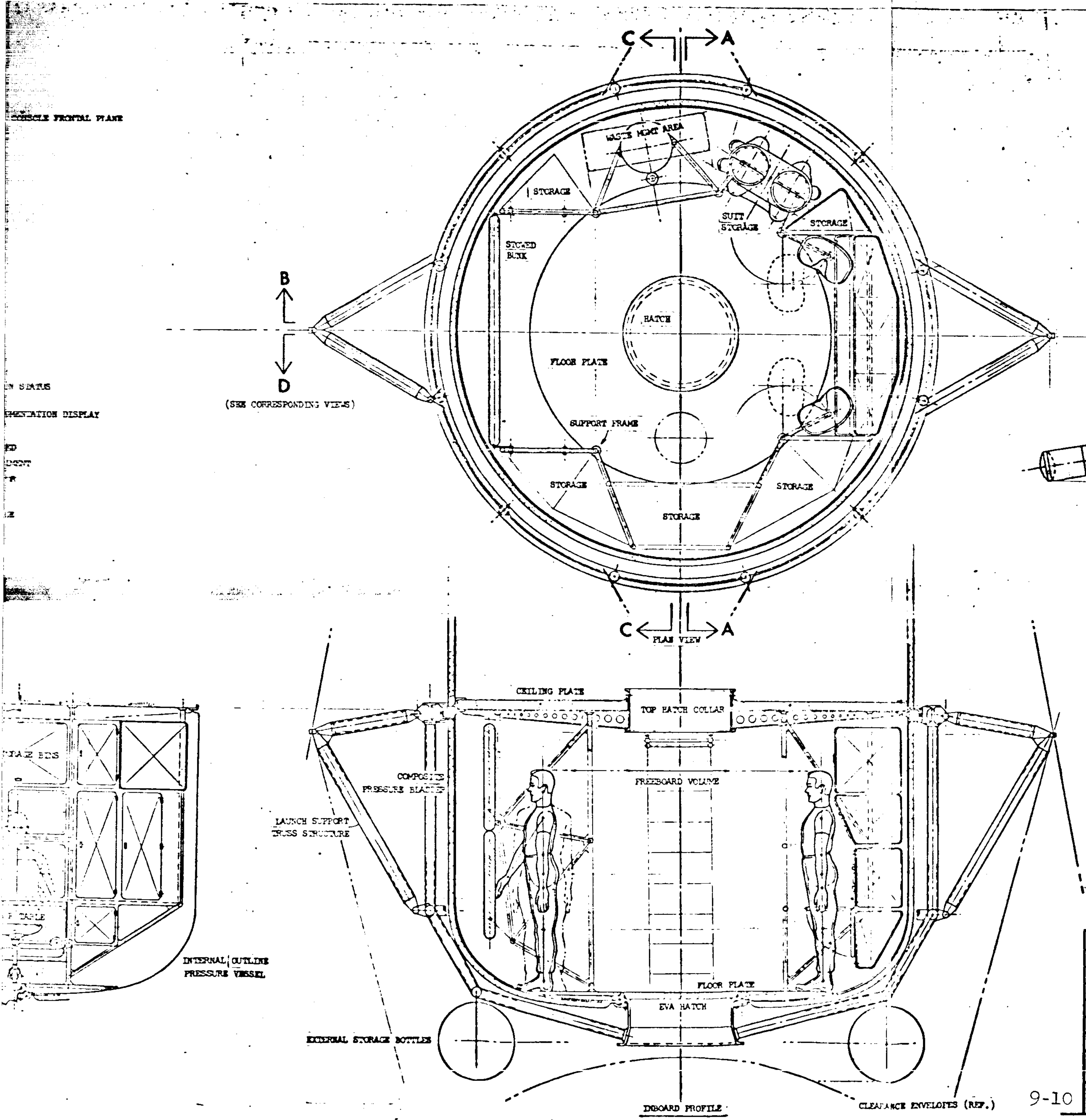
CONFIGURATION MD-4
FIGURE 9.6

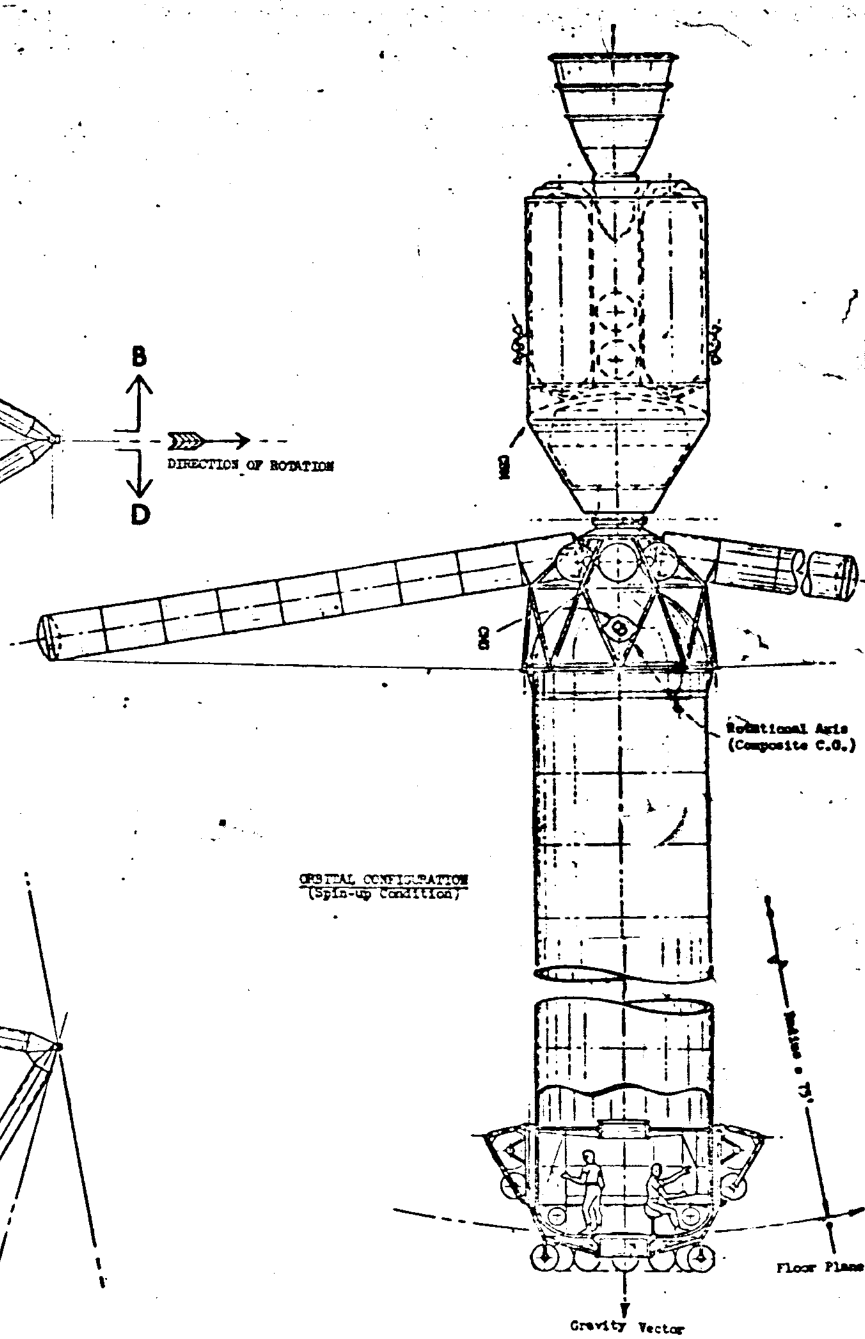
MD-4


Sta. 2680.0 (Ref.)
Rotational Axis (Composite C.G.)
Extended Structural Bag
Radius = 75'
Floor Plane
Gravity Vector
RCS
LES
CSM
CMG
Transposition Docking
Orbital Configuration (Spin-up Condition)
Restraining Cable
CSM (Manned)
154^D (Ref.)
SLA Deployment (Typ. 4 pl.)
Std Launch Outline
Revolv'd View
Docking (Sta. 1915) Interface
Std SLA
CMG (4)
Sepn. Plane
Sta. 1780.16
Sta 1698.68 (Ref.)
S-IVB LH_2 Dome
260^D (Ref.)
Launch Vehicle Compatability (Composite half-breadth)
Std. Clearance Outline
Moby-Dick Pkg.
Boom Cannister (2)
Inflation Bottles (6)
Deployed SLA Petals (4)
Plan View
Stabilizing Boom Cannister (2 Pl)
Docking Collar & Transfer Tube
Mass Container
Packaged Extensible Element (13:1 Pkg Factor)
Support Deck
Furbished Crew Quarters
Limp Pressure Bladder Extension
In Board Profile Launch Pkg.
Upper Support Cage Structure
Radiator Surface, 450 ft^2 Panels
Cryogenic Storage Bottles
Fuel Cell
Moby-Dick Payload Pkg
Mission Deployment of Extensible Element
Upper Terminal Ring
Separation Plane
Torroidal Snubber
Extensible
Continuous Pressure Bladder
Tangent Support Ring
Lower Terminal Ring
Module Extension Stroke
Launch Support Cage Structure (Upper Structure Similar)
Mission Activation of Crew Quarters (See Note 4)
75' R.
Eva Hatch
NOTES:
1. Single Saturn 1B Manned Launch for 14 day partial gravity experiment.
2. Concept features continuous pressure bladder between upper and lower terminal rings. Upper element extensible and packaged. Lower furbished element below tangent support ring in limp condition prior to inflation.
3. Extensible structure based on current and projected technology of LRC expandable orbital experiment module (Goodyear) prototype now under test.
4. Crew module has minimal interface with CSM. Furbished condition favors checkout and useful mission experiment time.
5. Preliminary layout, subject to analysis and system detail change.
National Aeronautics & Space Administration Manned Spacecraft Center - Houston, Texas
CONFIGURATION MD-5
FIGURE 9.7A
Conceptual Layout
ASTD SPD ETT



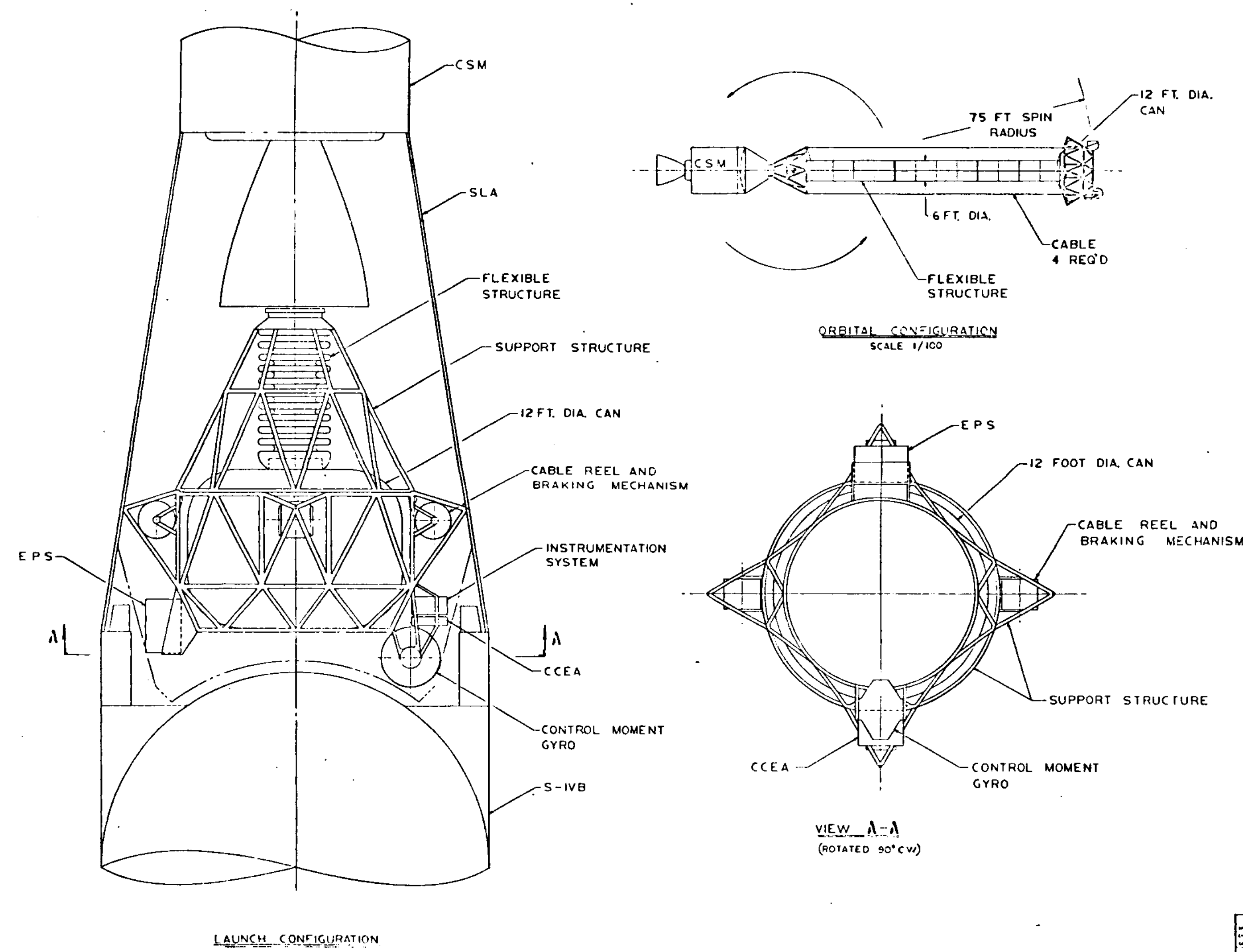
PLAN VIEW
ROTATIONAL SWEEP
BIO-MED EXPERIMENT AREA
STORAGE
BARANY CHAIR AND ERGOMETER MOUNTING LOCATION
LADDER
TILT SWEEP
SECTIONAL VIEW d
VIEW D-D
D
PRIVACY CURTAIN NOT SHOWN
SUIT STOWAGE AUXILIARY VIEW
PLAN VIEW
STORAGE
STOWED LADDER
REST AREA
WASTE MGMT. AREA
VIEW C-C
C
PLAN VIEWS
STORAGE
SIDE ELEVATIONS
CONTROL DUTY STATION, SINGLE OPERATOR
b SECTIONAL VIEWS
TYPICAL TUBULAR SUPPORT FRAMES
LOUNGE
VIEW B-B
B
VISUAL ENVELOPE OF SEATED OPERATOR
FIXATED NORMAL EYE
STATUS
DISPLAY
VIEW A-A
A





9-10

SIGNATURES		DATE	NATIONAL AERONAUTICS & SPACE ADMINISTRATION MANNED SPACECRAFT CENTER · HOUSTON, TEXAS
DR	W. TAUB	6-20-67	'MOBY DICK'
ENG			Crew Quarters Accommodations
CH			
APP			
AUTH			CONFIGURATION MD-5
LAYOUT			CODE IDENT NO. ASTD 2A6 · SIZE D · GENERAL ARRANGEMENT FIGURE 9.7B
ASTD SPO ETT			SCALE 1:20 · SHEET



MOBY DICK
CONFIGURATION MD-7
FIGURE 9.8

9.2.1 Station Operational Concept

Although the six configurations differ in structural arrangements, they are operationally similar. The booster launches the station into an elliptic orbit. Then the CSM separates and docks to the station. The station separates from the S-IVB and is injected into the desired orbit by the Service Module Propulsion System. The flexible structure is then extended to its full length and the station is spun-up by the Service Module Reaction Control System. After the station achieves the proper rotational rate and is stabilized, the experimental crewmen leave the Command Module and go to the Experiment Module part of the station. This necessitates their crossing the spin axis while the station is rotating.

Each configuration has three similar problems. The first is the fact that the experimental crewmen are separated from the Command Module by the full length of the station. This would preclude a rapid abort if some disaster should strike. The second is the very short spin radius that is imposed on the Command Module crewman. This would cause rather extreme stimulii to his vestibulo-proprioceptive sensing organs and could conceivably cause him to be ill during the entire mission. A third problem is the development of a non-flammable flexible structure. Limited quantities of a suitable non-flammable material exists; however, an intense development and procurement program must be initiated to meet the projected flight date.

If these three problems are not deemed serious, then the Moby Dick concept will provide an efficient artificial gravity space station.

9.2.2 Configurations

The configurations are shown on Figures 9.3 through 9.8. A distinct similarity can readily be seen in each of them, that of the truss structure attaching them into the Spacecraft LM Adapter (SLA).

The MD-1 and MD-2 configurations are similar in that they are attempts to utilize the Multiple Docking Adapter (MDA). This provides a diameter of 10 feet for each configuration. The subsystems and expendables are carried in the MDA both during launch and in orbit, which necessitates transferring equipment to the Experiment Module end. Since it was felt that this situation would impose unrealistic operational procedures on the crew, MD-3 was developed.

MD-3 utilizes the Subsystems Test Bed (STB) as an Experiment Module. This provides a 15 foot diameter for this configuration and the flexible structure becomes a transfer tube to provide the necessary station length. This concept requires additional structure to house the flexible structure and docking port; however, it does simplify the equipment installation.

MD-4 is a departure from the previous configuration in that it eliminates the "hard can" Experiment Module and substitutes a floor with flexible structure walls. The floor diameter also reduces to $12\frac{1}{2}$ feet. The subsystems are installed on a top deck which is attached to the support truss through the flexible structure walls. This necessitates long interface lines to the experiment end of the station. However, the required experimental gear is mounted on the floor of the Experiment Module and can be emplaced with less effort than the first two configurations.

The extendable stabilization booms were not added to this configuration because investigation indicated that they were not required for stabilization and control.

Configuration MD-5, second in the series of total flexible structure as opposed to combinations of flexible structure and metal, is the first to place all subsystems and equipment in the Experiment Module end of the station. This permits much easier operation and minimizes long wire runs to the Command Module. The 14 ft diameter of this configuration provides more than adequate floor area.

The flexible structure is held in place in the SLA with a large truss, which also holds the docking port and expendable tanks.

A support deck, supported by the truss through the flexible structure walls, provides the necessary rigidity in the Experiment Module and is the main support for the installation of equipment. The lower equipment support is the floor plate attached to the termination ring of the flexible structure; this ring also provides the hard structure for an EVA hatch, if one is desired.

Figure 9.7B shows the general arrangement of the equipment in the Experiment Module and how it is mounted to the support deck and floor plate.

Each work area is detailed sufficiently to show accessibility and orientation relationships with respect to the velocity vector.

The control station is arranged so that one man can operate the station, but is also large enough that both crewmen can work simultaneously. The stools stow out of the way when not required, and are extendable to use for either single or dual occupancy of the control station.

The bio-medical experiment area has a mounting bracket for the Barany chair and the ergometer. These items are stowed when not in use. Sufficient clearance for either experiment is available. The orientation with respect to the velocity vector is non-optimum, but should not interfere with the experiment nor affect the data.

The rest area is oriented properly with the velocity vector and consists of two bunks which can be stowed when not in use or arranged as a seat. Each crewman has a personal storage area in the vicinity of his bunk.

The waste management area is large enough for easy usage and can be isolated by curtains without affecting the remainder of the station.

Pressure suit storage is provided such that the suits are readily available.

Some of the experiments required for the artificial gravity study were not available at the time this configuration was designed and, therefore, are not shown in this general arrangement. It is believed, however, that they could be fitted into the configuration without a great deal of difficulty and that this arrangement, although incomplete, permits valid conclusions regarding equipment installation.

The final configuration, MD-7, is a culmination of the better ideas developed in the preceding configurations. The floor area was reduced to a 12 foot diameter. Very similar to MD-5, it surrounds a flexible structure Experiment Module with a tubular framework which also supports the exterior subsystems and the SLA attach structure. This framework further holds the docking port and provides containment for the flexible structure tunnel.

The basic difference between MD-7 and MD-5 is the smaller diameter tunnel. The MD-5 tunnel was the same diameter as the Experiment Module. It was felt that the larger diameter was needed for stiffness, but subsequent investigation disproved this and permitted the use of a lighter weight, smaller diameter tunnel.

Four cables, running from the docking port end of the station to the Experiment Module end, were added to this configuration to provide controlled extension of the flexible structure. This will limit the speed of extension and provide better control during spin-up.

9.2.3 Configuration Comparison

Table 9.1 shows the six Moby Dick configurations on a comparative basis. The comparative items can be categorized into quantative and qualitative areas.

The quantative areas are the most straight forward and easily developed. The structural weight, usable pressurized volume, floor area, and costs are familiar and need little explanation.

The floor area effectiveness factors are derived from the recommended space requirements in Section 3. By dividing the floor area, the configuration actually has, by the recommended and/or the minimum value, a comparative measure of the usable size of a station is achieved.

The MD-7 was selected as the Moby Dick configuration that best met the objectives of the study within the guidelines. Its floor area and volume were adequate; its basic equipment layout could be considered as meeting the standards established by Section 4; its weight was the least of all the configurations.

9.3 Cable-Connected Vehicle

Since the cable-connected vehicle concept was considered the most promising, its configurations were investigated and compared rather extensively. The extension mechanism was studied; it was determined that a single cable on a reel would be satisfactory. The control and stabilization problem was investigated; it was determined that a single control moment gyro would stabilize the system. The counterweight was studied; it was determined that the spent S-IVB stage on a comparatively short cable was more attractive than a smaller counterweight on a longer cable.

9.3.1 Station Operational Concept

All of the configurations are operationally similar. Figure 9.9 shows the concept in the Spin Plane Configuration.

The booster launches the station directly into orbit where the Command/Service Module separates, turns around, and docks to the Experiment Module. After the equipment is

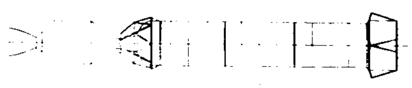
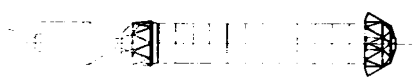
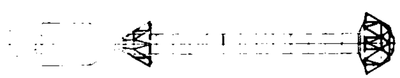
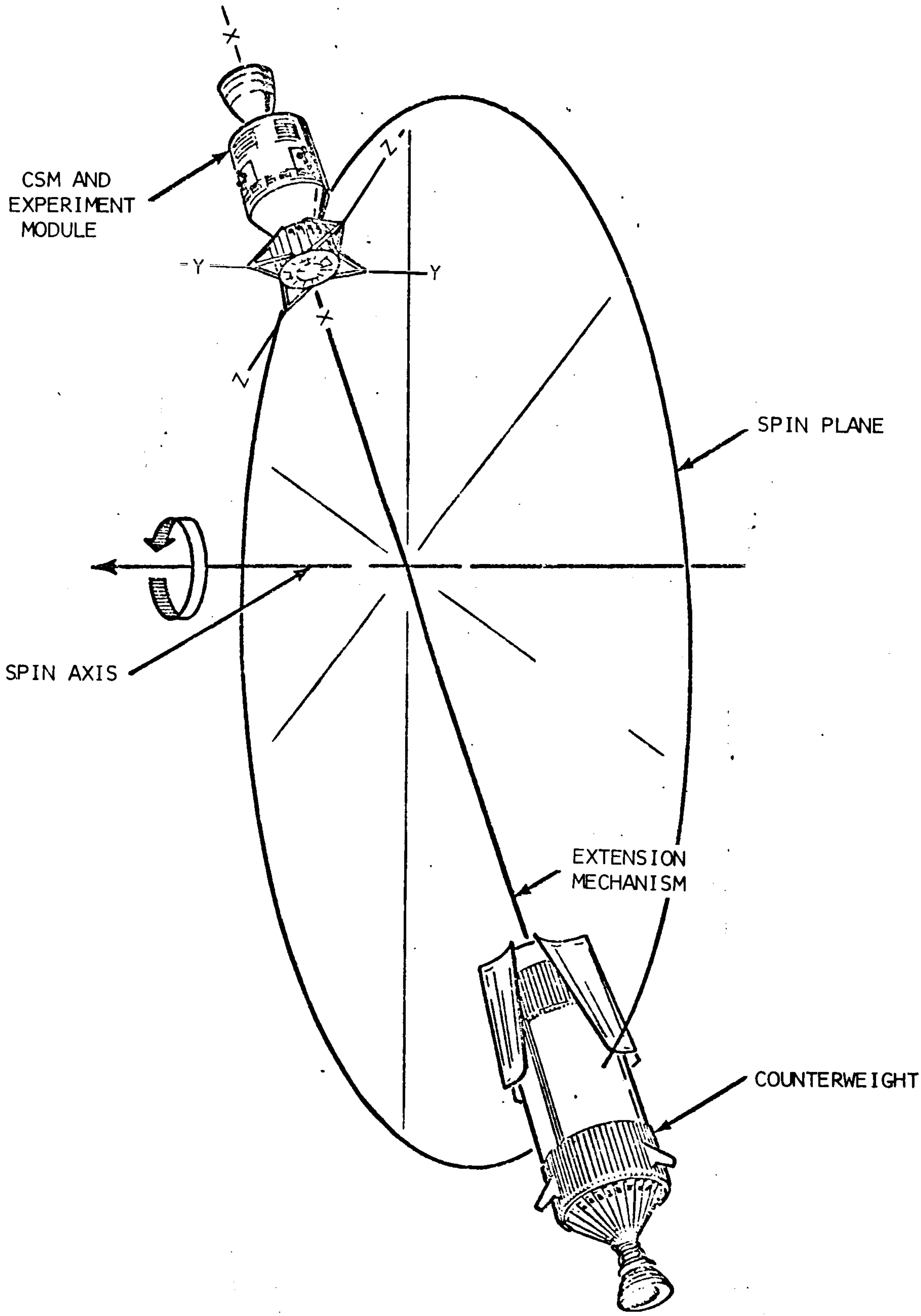
CONFIGURATION		STRUCTURAL WEIGHT (LBS)	PRESSURE VOLUME (FT^3)	FLOOR AREA (FT^2)	FLOOR AREA EFFECTIVENESS FACTORS		COMMENTS	COSTS, IN MILLIONS OF DOLLARS		
					EXISTING / RECOMMENDED	EXISTING / MINIMUM		NONRECURRING	RECURRING	TOTAL
MD-1 MD-2 MD-4		4612	5173	79	.848	1.019	. REPRESENTATIVE OF THREE CONFIGURATIONS, SHOWING EVOLUTION OF FLEXIBLE STRUCTURE CONCEPT.	4.23	1.66	5.89
MD-3		7593	10898	143	1.534	1.845	. ADAPTATION OF STB TO ARTIFICIAL GRAVITY. . 15 FOOT CAN (STB) EASILY FABRICATED, FLEXIBLE STRUCTURE DIFFICULT. . INTERIOR EQUIPMENT INTEGRATION PERHAPS COMPLEX DUE TO LOCATION OF SUBSYSTEMS, EXTERIOR STORAGE SIMPLE. . INERTIA DIFFERENCES BETWEEN Y AND Z AXES BUILT UP BY ADDING BOOMS, IF NECESSARY. . MINIMUM CHANGE TO CSM, LITTLE CHANGE TO STB, NO CHANGE TO SLA. . MINIMUM FUTURE USE EXCEPT IN ADDITIONAL ARTIFICIAL GRAVITY, SHORT DURATION EXPERIMENTS.	6.64	1.81	8.45
MD-5		4612	9403	123	1.319	1.587	. TOTAL FLEXIBLE STRUCTURE CONCEPT. . DIFFICULT TO DESIGN AND FABRICATE. . EQUIPMENT INTEGRATION SHOULD BE REASONABLE, BOTH INTERIOR AND EXTERIOR. . INERTIA DIFFERENCE IN Y AND Z AXES AIDED IMMEASURABLY BY ADDING EXTENDABLE WEIGHTS, IF REQUIRED. . MINIMUM CHANGE TO CSM, NO CHANGE TO SLA. . MINIMUM FUTURE USE IN AAP PROGRAM, EXCEPT FOR ARTIFICIAL GRAVITY EXPERIMENTS.	4.23	1.66	5.89
MD-7		2137	2915	113	1.212	1.458	. SAME AS MD-5 (ABOVE) EXCEPT FOR REDUCED DIAMETER EXTENDING TUBE. . ALL COMMENTS ABOVE APPLY, EXCEPT POSSIBLY MORE DIFFICULT TO DESIGN AND FABRICATE REDUCED DIAMETER TUBE.	3.01	1.21	4.22

TABLE 9.1



CABLE - CONNECTED VEHICLE

FIGURE 9.9

checked out, spin-up is started and rotation rate of 3 degrees per second is obtained while the Command-Service Module and Experiment Module are still rigidly attached to the S-IVB. Once the rotating system is checked out and stabilized, the S-IVB is released and the cable reeled out. When the desired spin radius is achieved, the station rotation speed is increased to the required rate and a second checkout is made. Only then will the Experiment Module crewmen transfer to the Experiment Module.

Since the Command Module is docked to the floor of the Experiment Module, its RCS thrusters providing the spin-up power are at a maximum distance from the spin axis. Also, the interface connections from the Command Module to the Experiment Module are minimized.

The Experiment Module has the experiments, controls, and necessary subsystems located to provide the maximum moment of inertia about the Z axis, as well as provide the crew with the most favorable orientation with respect to the tangential velocity.

The connecting cable reel is attached to the "roof" of the Experiment Module with a shock absorber mount. This mount provides angular rate damping of the Experiment Module with respect to the connecting cable. The cable reel is motorized to control the extension rate and to enable the crewmen to vary the gravity level if desired.

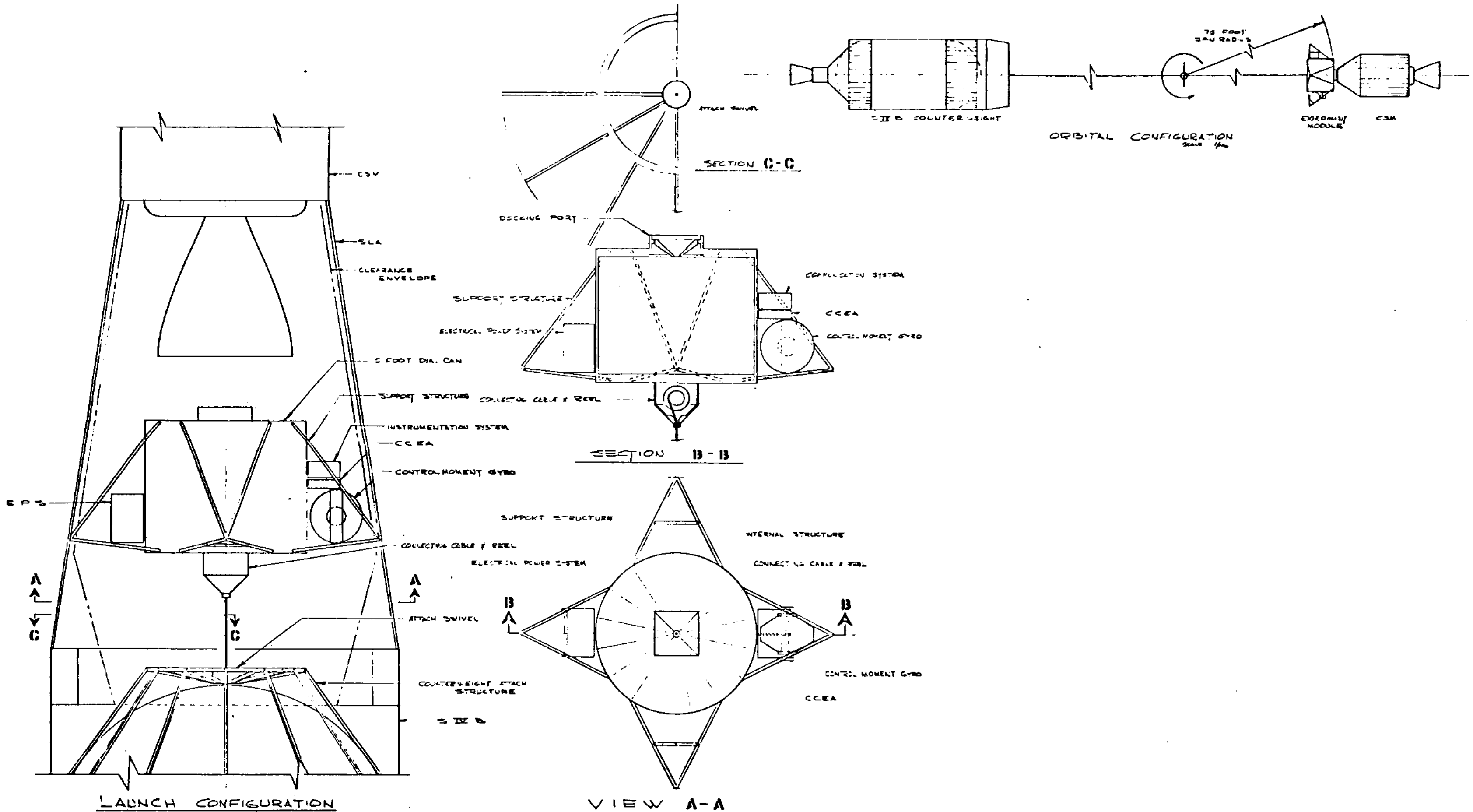
The connecting cable is attached to the S-IVB counterweight through a swivel, which prevents counterweight roll motions from being transmitted to the Experiment Module. The swivel is attached to the S-IVB through a "bridle" cable arrangement which limits the counterweight angular displacement.

The S-IVB is strictly passive and is utilized solely as a counterweight. All the activity takes place at one end of the station, which concentrates the equipment and simplifies the interface of the entire system.

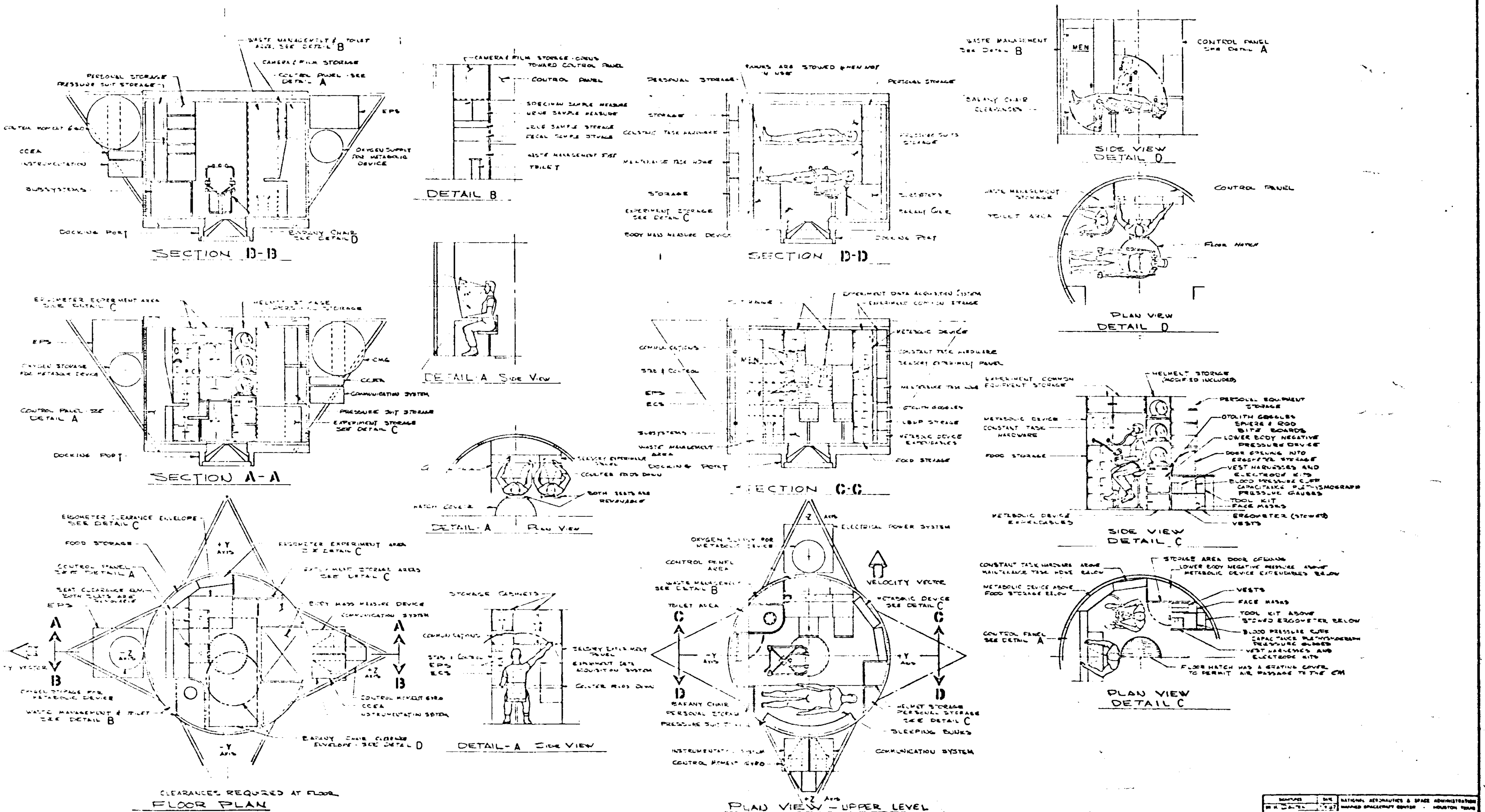
Thus, since the operational concept of all the configurations is similar, the investigation narrowed to a comparison of module shapes and floor diameters.

9.3.2 Configurations

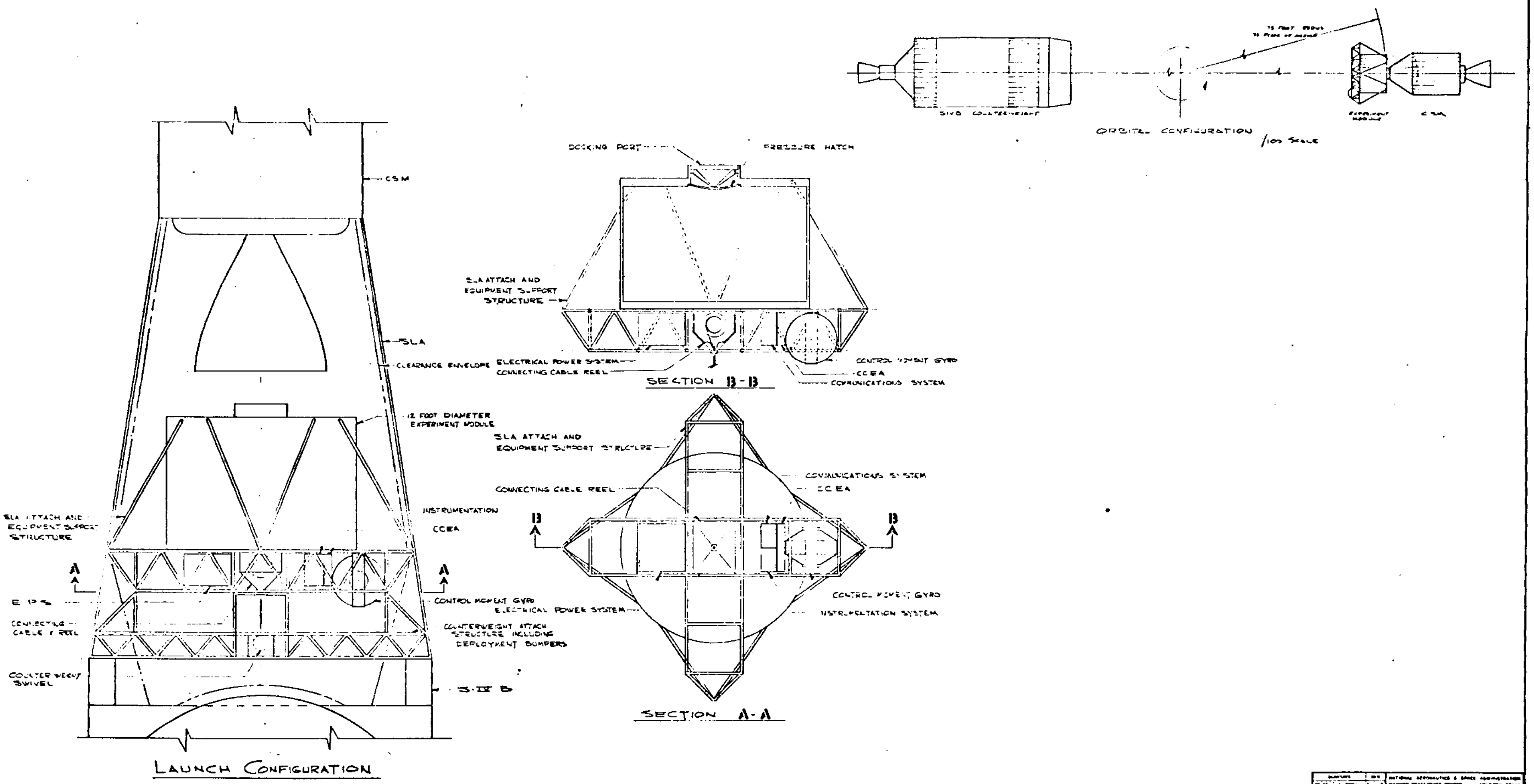
The cable-connected vehicle configurations are shown on Figures 9.10 and through 9.14. The first is the Ten Foot Diameter Experiment Module.



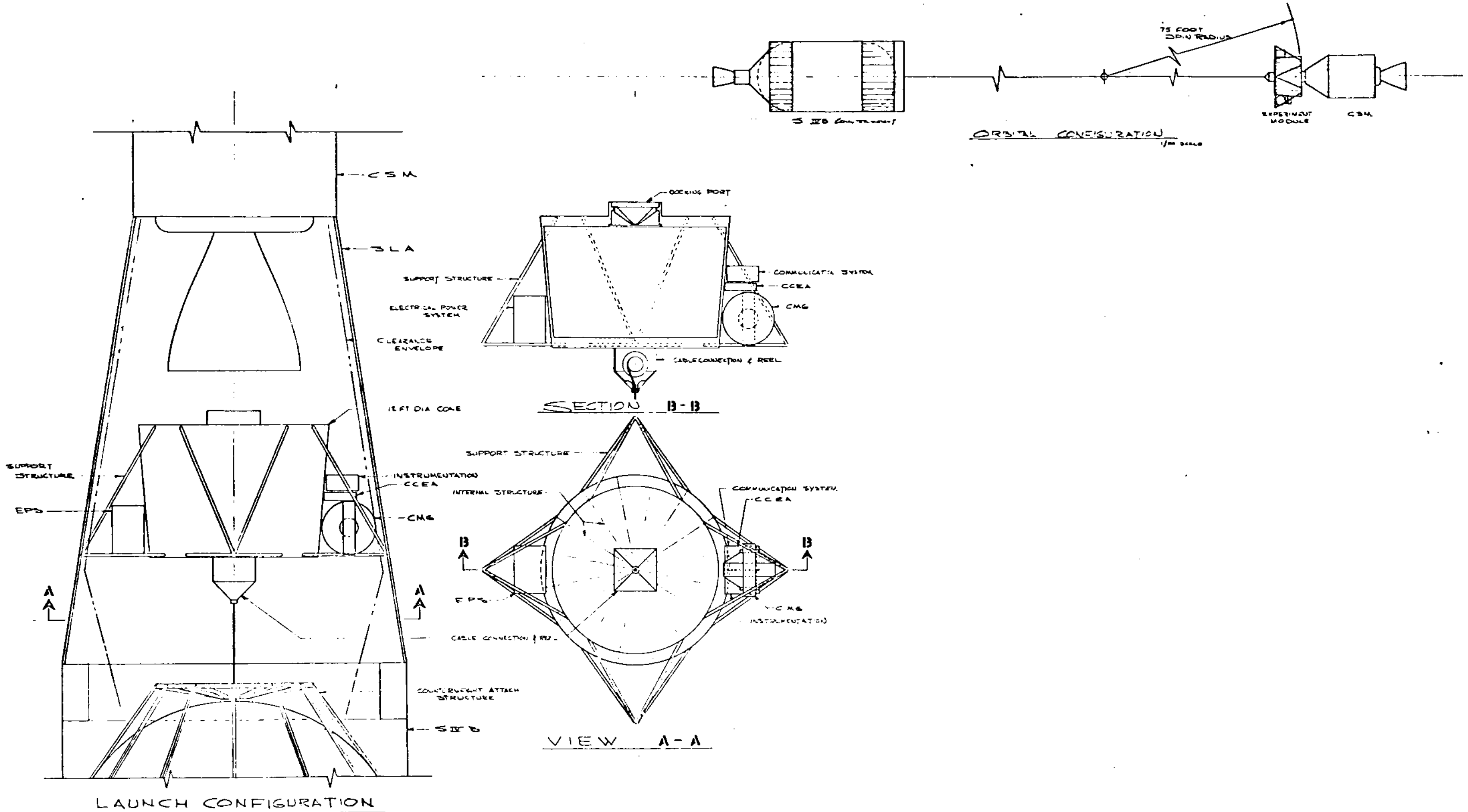
ARTIFICIAL GRAVITY
CONFIGURATION CCV-1
FIGURE 9.10A



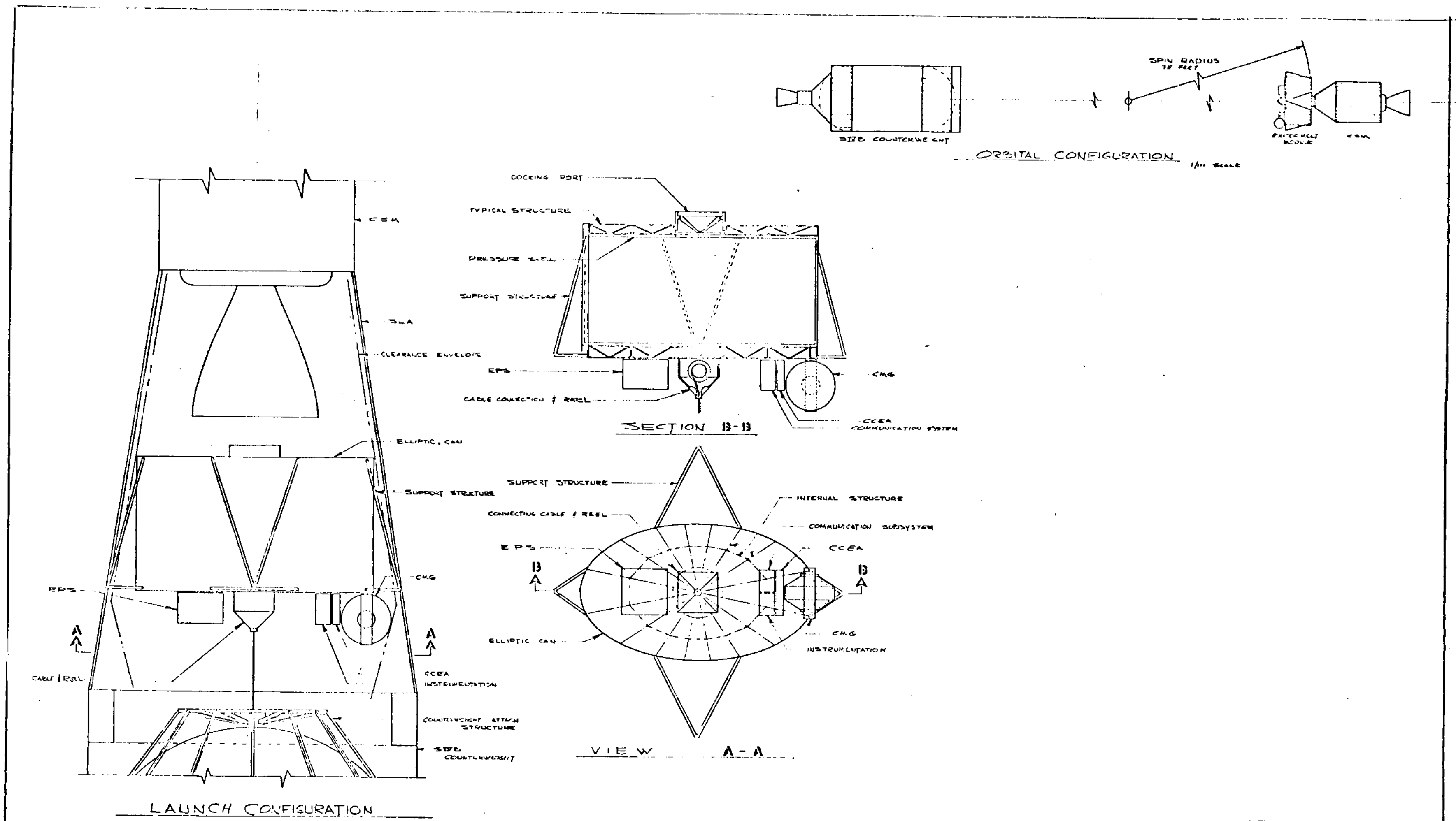
CONFIGURATION CCV-1
GENERAL ARRANGEMENT
FIGURE 9.10B



ARTIFICIAL GRAVITY
CONFIGURATION CCV-2
FIGURE 9.11



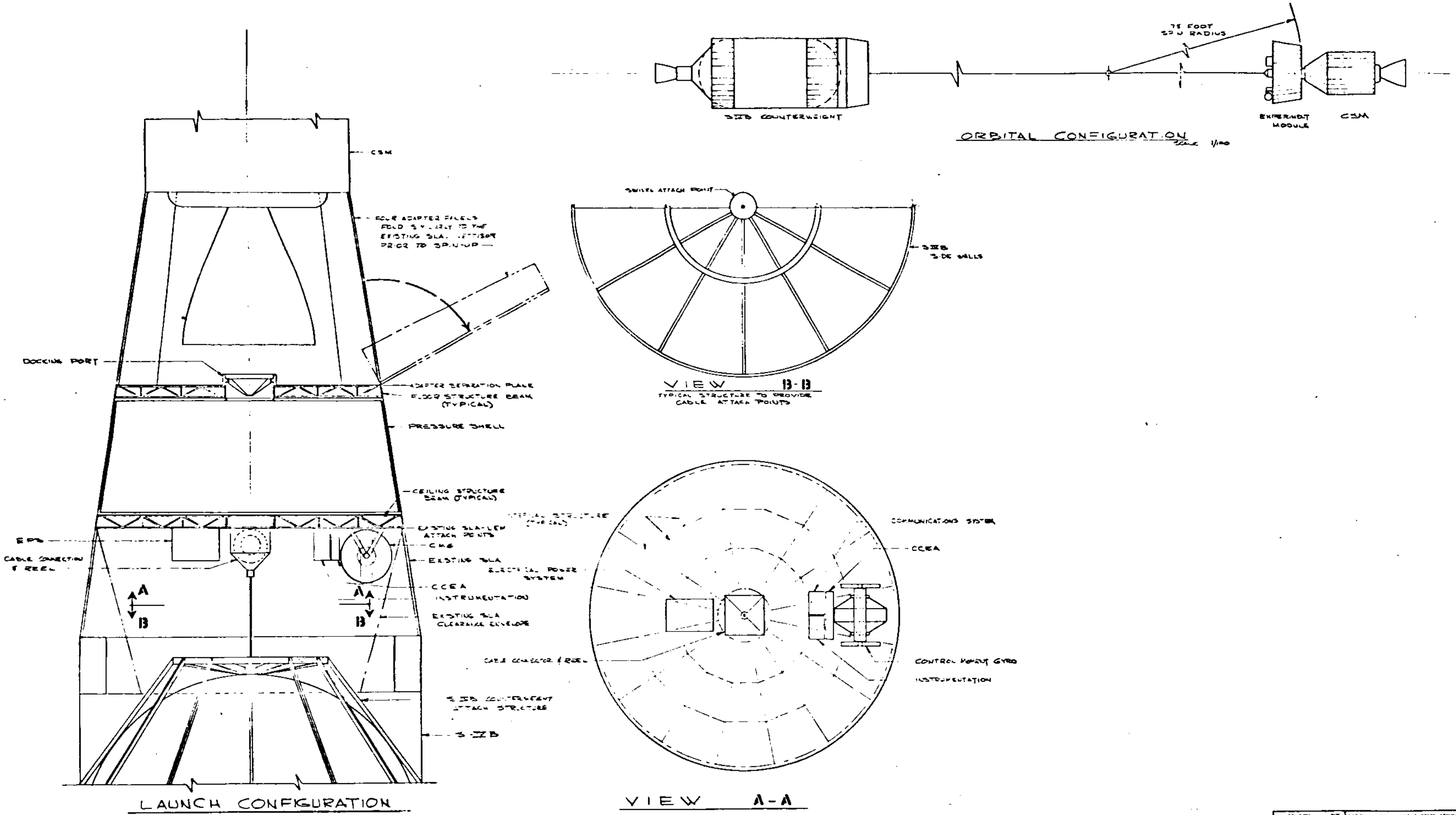
ARTIFICIAL GRAVITY
CONFIGURATION CCV-3
FIGURE 9.12



ARTIFICIAL GRAVITY

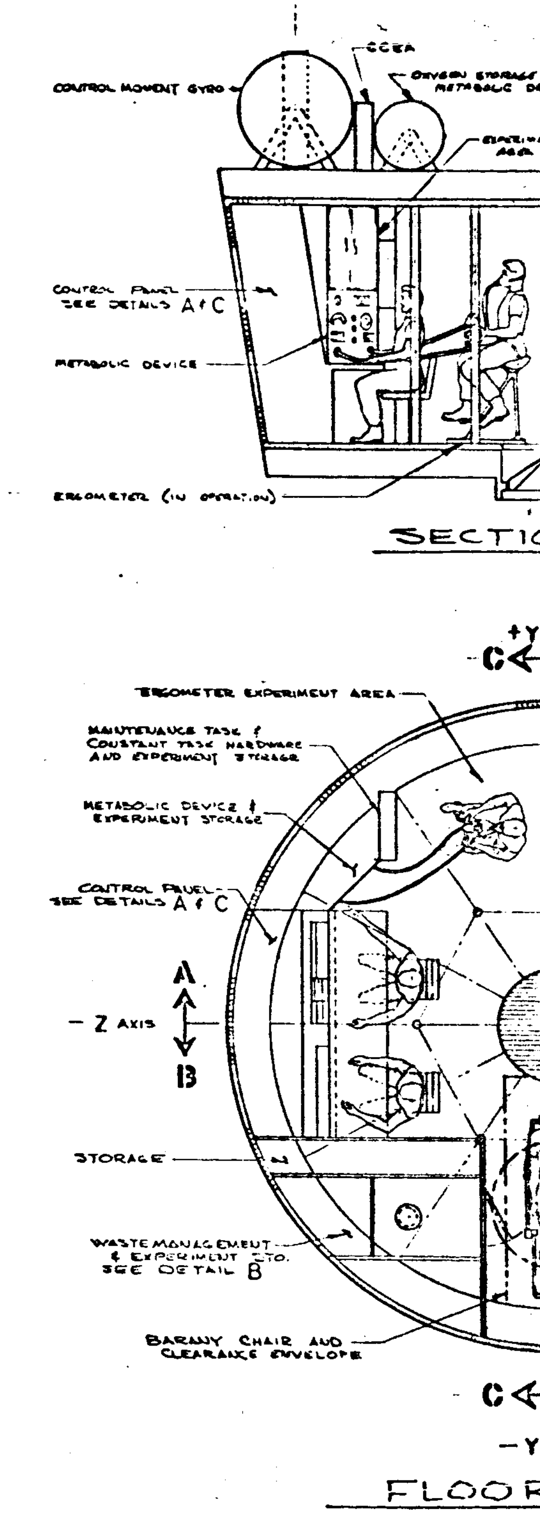
CONFIGURATION CCV-4

FIGURE 9.13

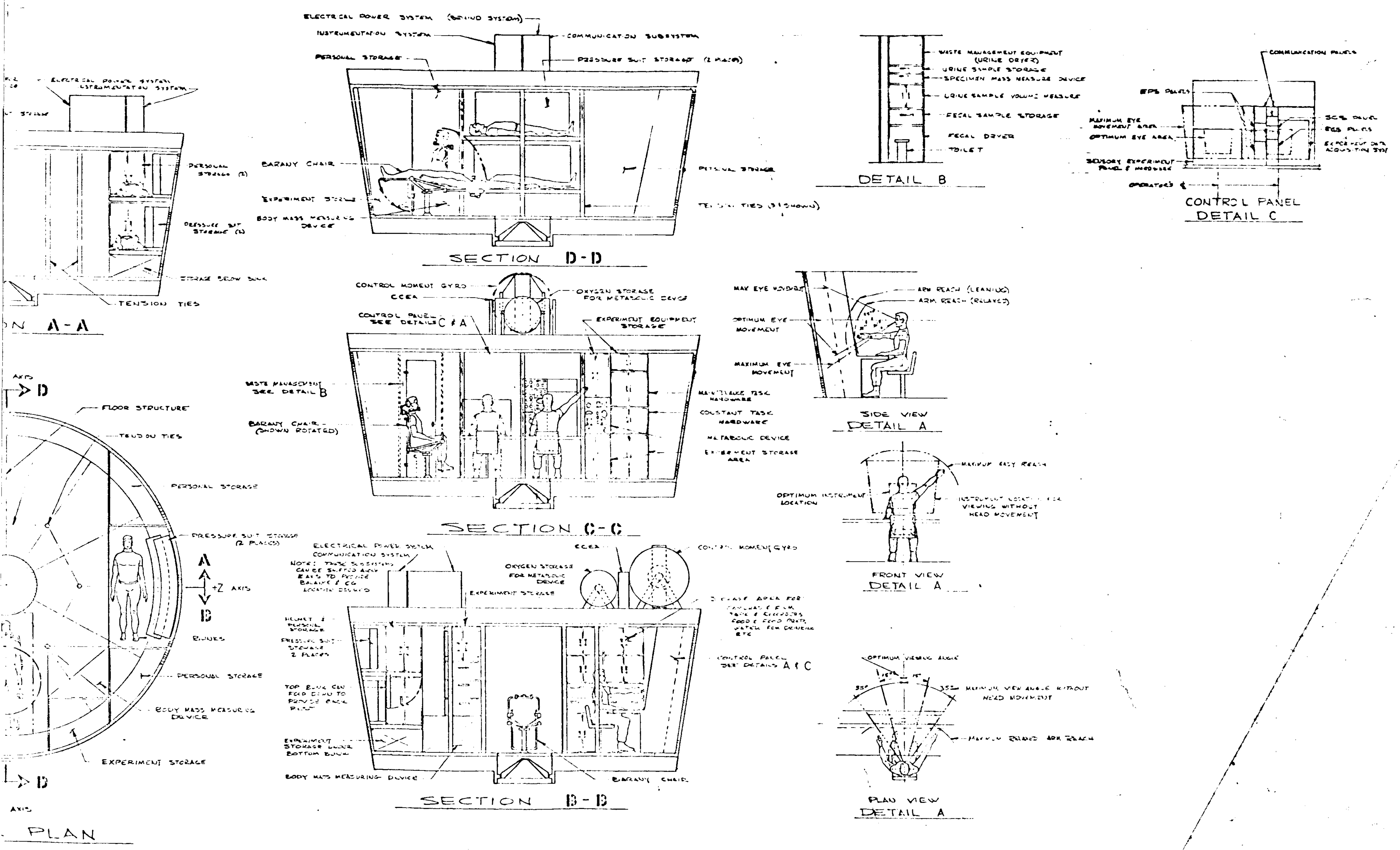


9-24

ARTIFICIAL GRAVITY
CONFIGURATION CCV-5
FIGURE 9.14A



CONTROL MOMENT GYRO
CONTROL PANEL SEE DETAILS A & C
METABOLIC DEVICE
ERGOMETER (IN OPERATION)
+Y
C
ERGOMETER EXPERIMENT AREA
MAINTENANCE TASK & CONSTANT TASK HARDWARE AND EXPERIMENT STORAGE
METABOLIC DEVICE & EXPERIMENT STORAGE
CONTROL PANEL SEE DETAILS A & C
A
- Z AXIS
B
STORAGE
WASTE MANAGEMENT & EXPERIMENT STO. SEE DETAIL B
BARANY CHAIR AND CLEARANCE ENVELOPE
C
-Y
FLOOR



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CONFIGURATION CCV-5
GENERAL ARRANGEMENT
FIGURE 9.14B

One of the inherent compromises common to all of the cable-connected artificial gravity concepts is readily apparent in Figure 9.10A. The module is upside down on the launch pad. This will present some minor difficulties in installing equipment in the module, as well as causing the structure to be stressed in both directions along the X axis during the mission. However, these problems are not considered to be of major significance and should not detract from the design of the module.

The general arrangement drawing (Fig. 9.10B) shows that the required equipment can be installed in the 10-ft module. The major work and experiment areas are oriented satisfactorily with the velocity vector; however, certain compromises are necessary to permit installation of the rest of the equipment. It is extremely compact, but even so, the experimental crewmen will have to lead fairly sedentary lives while in orbit.

The second design in the series is the Twelve-Foot Diameter Module. Since its floor area is slightly larger than the recommended minimum, it should provide a less constrained internal arrangement.

This module does not mount within the SLA as easily as did the previous configuration, but this is due to the mounting of the exterior equipment. If the equipment were attached directly to the "ceiling," the module mounting truss could be extremely simple.

However, since the exterior equipment would not fit in the truss structure as did the previous configuration, a cruciform truss structure that would provide a base upon which the module could rest, as well as provide a mounting rack for equipment, was developed. Further detailed design and analysis will be needed to determine whether or not this type of truss attachment is acceptable.

Since the Twelve-Foot Diameter Module did not permit neat packaging of the exterior equipment, a 12-ft diameter conical module was devised as the next step in the design. The objective was to provide sufficient space around the module to permit the installation of the exterior equipment while maintaining a 12-ft diameter floor. A 5 degree wall slope appears sufficient to accomplish this. (This is within the tolerances described in Section 4). Thus, a module is created that has the simplified attaching truss of the 10-ft module while maintaining the floor space of the 12-ft module.

The 12-ft conical module apparently combines the better features of both the previous designs, without undue compromise in weight or volume, and should prove attractive as an artificial gravity module.

For stability, any rotating, artificial gravity space vehicle requires a definite moment of inertia differential between the three axes. The cable-connected stations provide a good difference about the X axis; however, the moments of inertia about the Y and Z axes are inherently the same. The elliptic module is an attempt to alleviate this situation. The major axis of the ellipse is along the Z axis which provides favorable locations for mounting the equipment. The difference may be insufficient to counter the additional weight required for the module.

One inherent disadvantage in the elliptic module is that the interior space is available primarily along the Z axis (tangential velocity direction). This provides the maximum movement space in the direction least favorable to crew movement.

The 15-ft diameter STB was selected as a candidate configuration in this series. Since it is generally familiar, a drawing was not included in the document. However, a thorough weight breakdown, showing what items have been stripped from the original STB to lower its weight, is included in Section 10 (Weights). The "stripped" version is light enough to be considered in the ground rules of this study. An added attraction is the multi-use capability of the 15-foot diameter Experiment Module.

As an end point in the design of an artificial gravity module, a completely modified SLA Experiment Module was investigated. Such a configuration provides the maximum floor space available at a slight additional weight. It is readily seen from the general arrangement drawing, Figure 9.14B, that the interior equipment and work areas can be installed most favorably and left in permanent locations. This, of course, leads to the conclusion that the modified SLA Lab is usable for more than one type of experiment and has uses beyond the artificial gravity module.

It would seem that if the additional weight and cost of this configuration can be justified on the basis of excellent interior equipment arrangement and additional future use, the modified SLA concept can be very attractive as an artificial gravity module.

9.3.3 Configuration Comparison

Table 9.2 shows the six "cable-connected" configurations on a comparative basis. The items compared are similar to

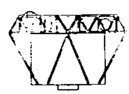
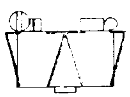
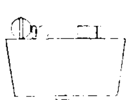
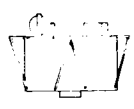
	CONFIGURATIONS	STRUCTURE WEIGHT (LBS)	VOLUME (FT^3)	FLOOR AREA (FT^2)	FLOOR AREA EFFICIENCY FACTORS		COMMENTS	COSTS, MILLIONS OF DOLLARS		
					EXISTING / RECOMMENDED	EXISTING / MINIMUM		NONRECURRING	RECURRING	TOTAL
1	 10 FOOT MODULE	2600	655	79	0.85	1.02	. SIMPLE DESIGN AND FABRICATION. . INTERIOR EQUIPMENT INTEGRATION COMPLEX DUE TO MINIMUM VOLUME, EXTERIOR EQUIPMENT INSTALLS READILY IN TRUSS. . INERTIA DIFFERENCE IN Y AND Z AXES IS SMALL DUE TO MINIMUM VOLUME. . CG CHANGES SIMILAR FOR ALL CONFIGURATIONS. MINIMUM IMPACT ON EXISTING HARDWARE. . CAN BE USED FOR ANY FUTURE TWO-MAN EXPERIMENT, EITHER ZERO OR ARTIFICIAL GRAVITY OF LIMITED DURATION.	7.51	1.40	9.91
2	 12 FOOT MODULE	3200	942	113	1.21	1.46	. SIMPLE DESIGN AND FABRICATION. . INTERIOR EQUIPMENT INTEGRATION EASIER THAN 10 FOOT MODULE, EXTERIOR EQUIPMENT MOUNTS TO "CEILING," MAY CAUSE SLIGHT DESIGN PROBLEMS. . INERTIA DIFFERENCE IN Y AND Z AXES MAY BE GREATER THAN 10 FOOT MODULE BECAUSE OF LARGER VOLUME. . MINIMUM IMPACT ON EXISTING HARDWARE. . CAN BE USED FOR ANY FUTURE TWO-MAN, ZERO OR ARTIFICIAL GRAVITY EXPERIMENT, OF LIMITED DURATION.	8.83	1.64	10.47
3	 12 FOOT CONE	3100	842	113	1.21	1.46	. SIMPLE DESIGN AND FABRICATION. . INTERIOR EQUIPMENT INTEGRATION SIMPLER THAN 10 FOOT MODULE, MORE COMPLEX THAN 12 FOOT MODULE. EXTERIOR EQUIPMENT INSTALLS EASILY IN TRUSS. . INERTIA DIFFERENCES IN Y AND Z AXES PROBABLY SIMILAR TO 12 FOOT MODULE. . MINIMUM IMPACT ON EXISTING HARDWARE. . CAN BE USED FOR ANY FUTURE TWO-MAN, ZERO OR ARTIFICIAL GRAVITY EXPERIMENT OF LIMITED DURATION.	10.55	1.71	12.26
4	 ELLIPTICAL MODULE	3400	696	111	1.19	1.43	. DESIGN AND FABRICATION MORE COMPLEX. . INTERIOR EQUIPMENT INTEGRATION SIMPLE, EXTERIOR EQUIPMENT SHOULD BE ATTACHED TO "CEILING" TRUSS, TO PROVIDE MAXIMUM INERTIA DIFFERENCE. . INERTIA DIFFERENCE IN Y AND Z AXES MAXIMUM DUE TO AVAILABLE VOLUME AND PLAN FORM. . MINIMUM IMPACT ON EXISTING HARDWARE. . USEFUL FOR ANY FUTURE THREE-MAN, ZERO OR ARTIFICIAL GRAVITY EXPERIMENT OF SHORT DURATION OR A TWO-MAN EXPERIMENT UP TO 25 DAYS IN ORBIT.	12.13	1.61	13.74
5	 SLA ADAPTER LAB	4000	2284	218	2.38	2.82	. REASONABLE DESIGN AND FABRICATION. . INTERIOR EQUIPMENT INTEGRATION EASY, EXTERIOR EQUIPMENT MUST BE ATTACHED TO "CEILING" TRUSS. . INERTIA DIFFERENCE BETWEEN Y AND Z SHOULD BE MAXIMUM DUE TO VOLUME AVAILABLE. . COMPLETE REDESIGN OF SLA. . USEFUL FOR ANY FUTURE ZERO OR ARTIFICIAL GRAVITY EXPERIMENT OF FROM TWO MEN FOR [illegible] DAYS TO SEVEN MEN FOR TEN DAYS.	11.32	2.07	13.39
6	 SYSTEMS TEST BED	3375	1290	177	1.91	2.29	. THERMAL TEST PROTOTYPE BEING MANUFACTURED. . INTERIOR EQUIPMENT INTEGRATION EASY, EXTERIOR EQUIPMENT MUST BE ATTACHED TO "CEILING" TRUSS. . INERTIA DIFFERENCE BETWEEN Y AND Z AXIS CAN BE MAXIMUM. . USEFUL FOR FUTURE ZERO OR ARTIFICIAL GRAVITY EXPERIMENTS FOR FROM 2 MEN FOR 30 DAYS TO 4 MEN FOR 8 DAYS.	10.11	1.16	11.27

TABLE 9.2

those used in Section 9.2.3 (Moby Dick configuration comparison).

Any of the configurations depicted, with the exception of the "modified SLA" will provide an adequate experimental module at a weight that permits a sufficient growth margin. The 12-foot diameter module was selected as representative of this concept.

It must be emphasized that the quantitative comparison factors are not necessarily exact. Much more detailed study is necessary to make the weights, costs, volumes, and floor areas sufficiently refined to reflect a high degree of confidence. However, since all of the quantitative numbers have been calculated similarly, it is believed that the conclusions reached are valid.

9.4 Concept Comparison

All of the configurations of each concept were evaluated against the set of factors established on Table 9.3. The most significant of these seemed to be the weight, cost, gravity levels obtainable, and operational safety. Accordingly, the status of the concepts within these four areas is shown on Table 9.4.

Obviously, the most important factor for comparison is the crew safety. The men must be separated, two in the Experiment Module and one in the Command Module, but in case of an emergency, the Experiment Module crewmen must be able to get to the Command Module rapidly and easily.

The Cluster and the Moby Dick concepts violate this precept by having the Experiment Module and the Command Module at opposite ends of the rotating system. Thus, in emergencies, the Experiment Module crewmen must traverse a tunnel of some kind (which may be gyrating wildly); cross the spin axis, with its attendant Coriolis effect; and crawl to the Command Module. They may not have sufficient time to accomplish all of these actions. The cable-connected concept, on the other hand, has the Command Module docked to the floor of the Experiment Module. The crewmen need only to drop through the hatch to reach it.

The cable-connected vehicle is the recommended concept because of the operational crew safety, variable gravity levels obtainable, and the gravity level in the Command Module. It was felt that the cost and weight were not enough higher than those of the Moby Dick to offset the vastly improved safety factor.

CONCEPT COMPARISON FACTORS

. HARDWARE

- . USEABLE PRESSURIZED VOLUME
- . USEABLE FLOOR AREA
- *. PERCENT WEIGHT GROWTH AVAILABLE
- *. GRAVITY LEVELS OBTAINABLE
- . SAFETY

. OPERATIONAL COMPARISONS

- . LAUNCH PAD
- . ORBIT
- . ABORT
- *. SAFETY

. GENERAL

- . ADVANCEMENT IN FABRICATION TECHNIQUES
- . TECHNOLOGY GAINED
- . TESTING REQUIRED

*. COSTS

* MOST SIGNIFICANT FACTORS

TABLE 9.3

CONCEPT COMPARISON

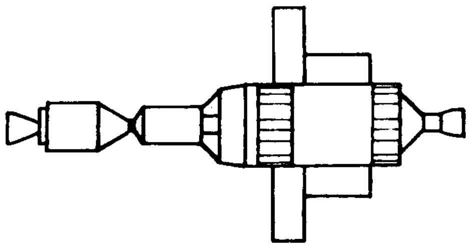
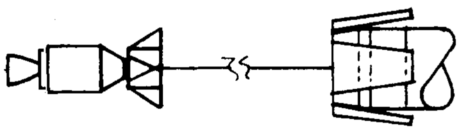
CONCEPT	PERCENT WEIGHT GROWTH AVAILABLE	COSTS MILLIONS OF DOLLARS	GRAVITY LEVELS AVAILABLE	OPERATIONAL SAFETY
 CLUSTER	~	~	MODULE - 0.18 "G" AT 3.4 RPM CSM - LESS THAN 0.05 "G" AT 3.4 RPM SPIN RADIUS FIXED	EXPERIMENT CREWMEN 40 TO 50 FEET FROM CSM CSM CREWMAN SUBJECTED TO DEBILITATING CORIOLIS EFFECTS
 MOBY DICK	48%	43.33	MODULE - 0.3 "G" AT 3.4 RPM CSM - LESS THAN 0.05 "G" AT 3.4 RPM SPIN RADIUS FIXED	EXPERIMENT CREWMEN 80 FEET FROM CSM CSM CREWMAN SUBJECTED TO DEBILITATING CORIOLIS EFFECTS
 CABLE-CONNECTED VEHICLE	18%	52.33	MODULE - 0.3 "G" AT 3.4 RPM CSM - 0.34 "G" AT 3.4 RPM SPIN RADIUS VARIABLE	EXPERIMENT CREWMEN IMMEDIATELY ADJACENT TO CSM CSM CREWMAN HAS LOW CORIOLIS EFFECT

TABLE 9.4

10.0 WEIGHTS

10.1 PAYLOAD CAPABILITY

Payload weight available for the Experiment Module may be obtained from Figure 10.1 for the cable-connected S-IVB counterweight configuration. Weights are shown for mission length from 8 to 14 days. Since orbit altitude has no direct impact on the experiment program, it has been assumed that the initial altitude will be just sufficient to maintain orbital flight for the duration of the mission. CSM weight is 25,300 pounds including retro-propellant. Direct injection into the final orbit by the launch vehicle is used to avoid the excessive loads on the docking interface which would result if the SPS were used for orbit injection of the CSM/EM/S-IVB combination.

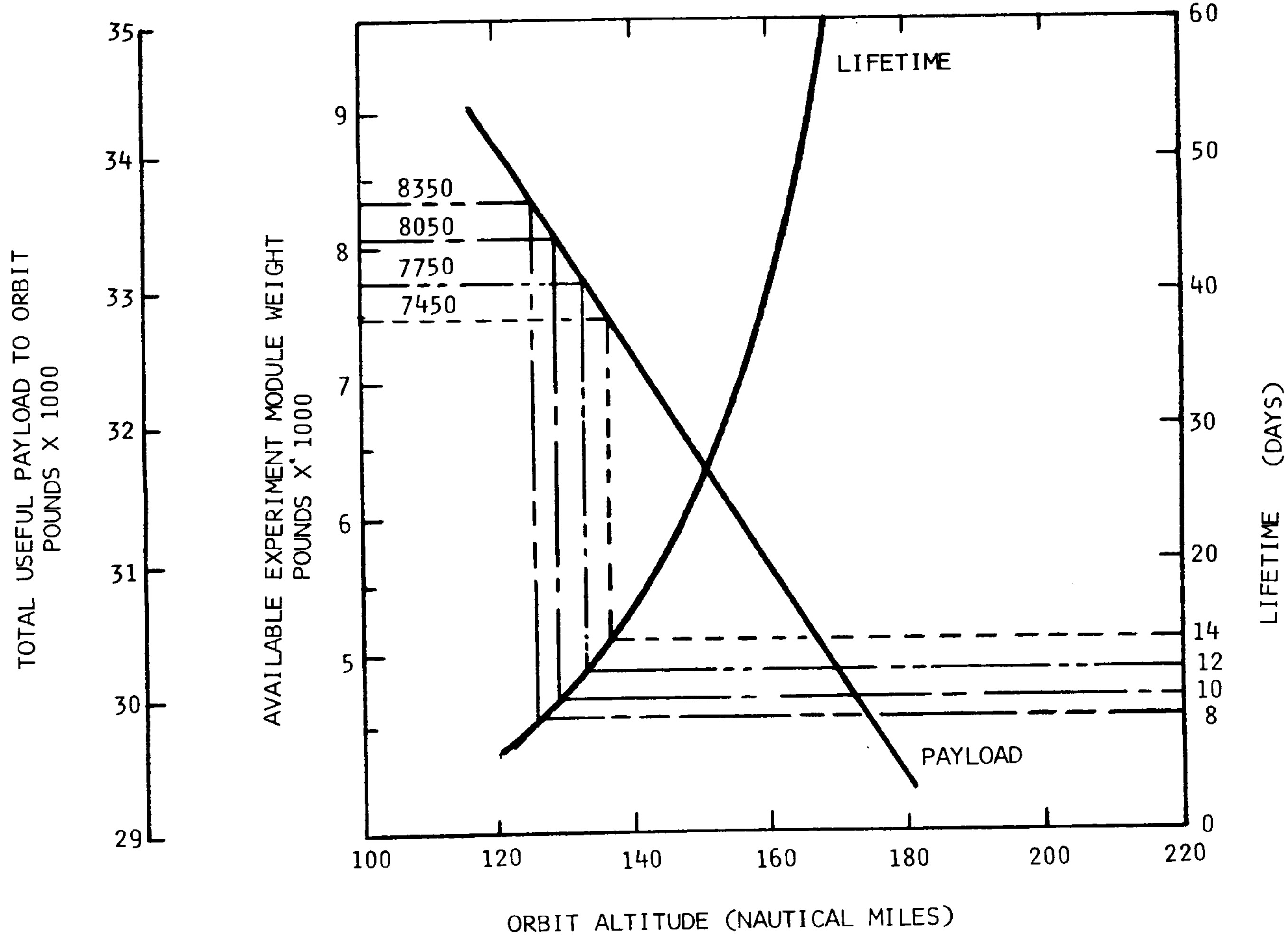
Figure 10.2 gives payload capabilities for the Moby Dick configuration. In this case, the SPS can be used for transfer from a low initial orbit to the final orbit, resulting in a substantial increase in payload.

10.2 EXPERIMENT MODULE WEIGHTS

Table 10.1 summarizes the estimated weights of the various EM configurations studied. Pressurized structure weights have been estimated using techniques developed by the Weights Engineering Section of Advanced Spacecraft Technology Division from historical data. Configuration 6 structure weight was based on the Subsystem Test Bed(STB) with reductions for 7 psia design pressure, no unnecessary stiffness in bulkheads, and deletion of various items (see Table 10.2) which are not applicable to EM requirements. Structural weight is the only item which was found to depend significantly upon configuration. Experiment and subsystem weights have been discussed Sections 5 and 6. Inflatable sturcture configurations are summarized in Table 10.3.

10.3 WEIGHT GROWTH

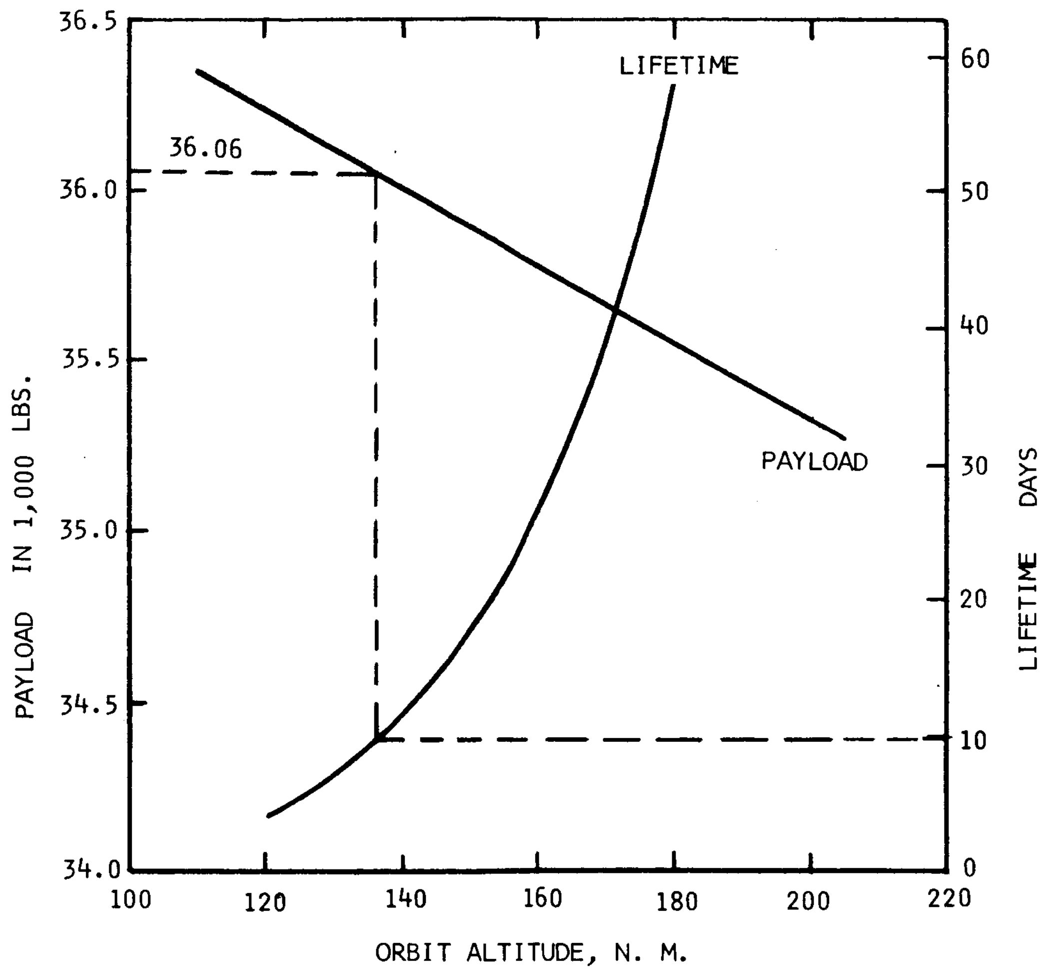
If estimated payload weight is less than the maximum payload capability of the booster, the difference (allowable weight growth) can be expressed as a percentage of estimated weight. Figure 10.3 shows this relation for the maximum payloads for 8, 10, 12, and 14 day missions. The horizontal lines represent estimated weights for various S-IVB counterweight configurations (first number) and mission length(second number). The intersection with the appropriate mission length curve gives the percent weight growth that can be tolerated. Previous experience indicates that at least 20% weight growth should be anticipated from the conceptual phase to the operational phase. Therefore, only intersection points to the right of the 20% line should be considered feasible. On this basis, only configurations 1 and 3 are capable of a 10-day mission. Configurations 2, 4, and 6 would be satisfactory for an 8-day mission since the estimated weight is the same for 8 and 10 days.



NOTES:
1. DIRECT CIRCULAR ORBIT INJECTION WITH S-IVB.
2. 28.5° ORBIT INCLINATION.
3. 1962 U.S. STANDARD ATMOSPHERE WITH MSFC DENSITY CORRECTION.

ARTIFICIAL GRAVITY
CABLE - CONNECTED VEHICLE
WEIGHT ALLOWANCE

FIGURE 10.1



NOTES:

1. ELLIPTICAL PARKING ORBIT WITH SM CIRCULARIZATION.
2. PAYLOAD EQUALS CSM AND EXPERIMENT MODULE.
3. 1962 U.S. STANDARD ATMOSPHERE WITH MSFC DENSITY CORRECTION.
4. 28.5 DEGREES ORBIT INCLINATION.

ARTIFICIAL GRAVITY
MOBY DICK - INFLATABLE STRUCTURE
WEIGHT ALLOWANCE

FIGURE 10.2

CABLE-CONNECTED VEHICLE
PRELIMINARY ESTIMATED WEIGHT COMPARISON

	1 10' MODULE	2 12' MODULE	3 12' CONE	4 ELLIPTICAL	5 SLA LAB	6 BSM
TRUSS	400	400	400	400	*	400
PRESSURIZED STRUCTURE	2200	2800	2700	3000	4000	2975
SUBSYSTEM SUPPORT STRUCTURE	241	241	241	241	241	241
EXPERIMENT SUPPORT STRUCTURE	65	65	65	65	65	65
EXTENSION MECHANISM	430	430	430	430	430	430
SUBSYSTEMS--EXPERIMENT (BASIC)	2857	2857	2857	2857	2857	2857
	6193	6793	6693	6993	7598	6968

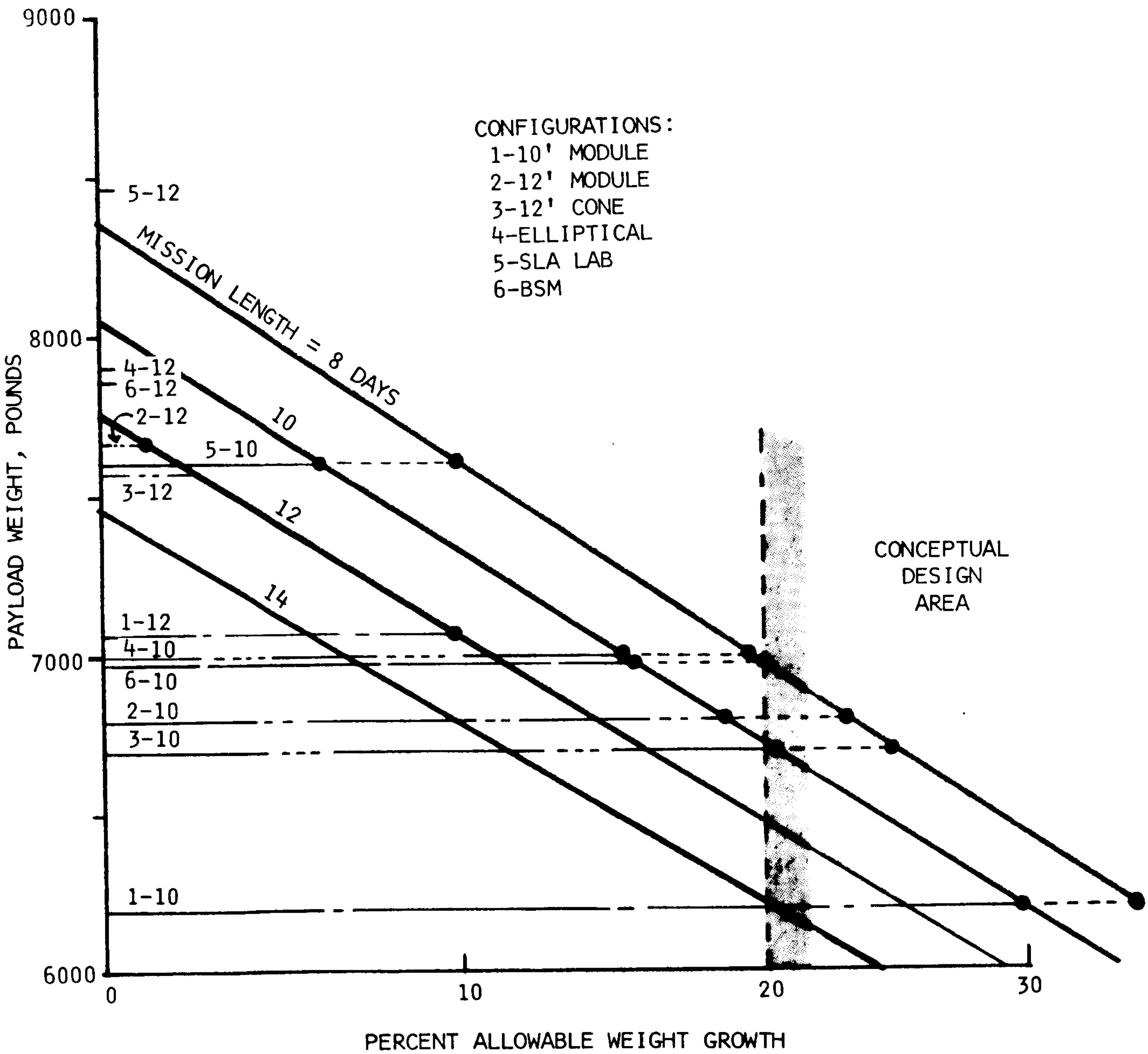
* TRUSS WEIGHT INCLUDED IN STRUCTURE WEIGHT

TABLE 10.1

WEIGHT ESTIMATE
ARTIFICIAL GRAVITY STB

"TEST ARTICLE" STB		5,200
EXTERNAL PRESSURE FRAMES	70	
BLANKOFF PLATES	220	
SIDE ACCESS DOOR	25	
ACOUSTIC INSULATION	61	
REMOVABLE FLOORS	127	
CRACK STOPPERS	80	
HARDPOINT AND FEEDTHROUGHS	69	
TRUSS	50	
PRESSURE	500	
"FLEXIBLE" BULKHEADS	380	
DOCKING EXTENSIONS DELETED	50	
SIDE DOCKING BEAMS DELETED	160	
HATCH & WINDOW COVERS, MOTORS, ETC.	150	
THREE DOCKING PORTS DELETED SIX WINDOWS DELETED	283	
TOTAL DELETIONS		2,225
TOTAL STRIPPED STB		2,975

TABLE 10.2



ALLOWABLE WEIGHT GROWTH

FIGURE 10.3

MOBY DICK
PRELIMINARY ESTIMATED WEIGHT COMPARISON

	MD-1,2,4	MD-3 (STB)	MD-5	MD-7 (6' TUNNEL)
TRUSS	200	225	200	200
DOCKING STRUCTURE	100	*	100	100
UPPER-LOWER FLOORS	550	*	550	550
EXPANDABLE TUNNEL	3370	3354	3354	1617
WORK AREA STRUCTURE	392	4710	392	392
DEPLOYMENT-RESTRAINT	198	198	198	198
SUBSYSTEMS-EXPERIMENTS (BASIC)	3370	3370	3370	3370
ADDED SUBSYSTEM FOR LONGER INTERFACE	170	170	170	170
TOTALS	8350	12027	8350	6597

* INCLUDED IN WORK AREA STRUCTURE WEIGHT

TABLE 10.3

11.0 COST ANALYSIS

The basic objective of this cost analysis was analogous to that of the technical study. To compare, on an absolute cost basis, the various methods of achieving artificial "g" in earth orbit and to estimate the total program cost for the selected configuration.

11.1 Total Program Costs

The total program costs of the recommended configuration (the 12 ft. diameter Experiment Module on a single cable extension mechanism) are indicated on Table 11.1. This total program includes design, development, testing and fabrication of one flight article experiment module, including systems, plus the required CSM integration and S-IVB modification costs. Not included are such costs as E&D support, experiment costs, tracking, control, or data analysis and retrieval costs.

Since the S-IVB modifications are considered very minor, the costs reflect only the design and fabrication of the cable mechanism and do not include any allowance for passivation of the S-IVB.

11.2 CSM Integration Costs

Since CSM integration tasks are estimated to be quite similar to those on the AAP 1A Mission, the cost for this effort is the same. Table 11.2 indicates these costs and the CSM modifications. These estimates were based on past ASTD studies, data from other E&D divisions, and North American-Rockwell proposals and estimates. For example, the SLA mods are quite similar to those once proposed on the AAP Orbital Workshop mission.

One significant cost is the $3.250\bar{M}$ which is for CSM mission planning and analysis. This results from the assumption that this flight uses one of the alternate Apollo CSM's, although, actually, if the experiment and mission is an artificial "g" mission from inception, this cost will not be incurred.

11.3 Total Program Cost Comparison

The comparative costs of alternate methods of achieving artificial "g" are shown in Table 11.3 where the recommended configurations of the two concepts were costed. In this table, the basic subsystem costs are assumed to be the same. The cost differences are in the structure subsystem, which

	NON-RECURRING	RECURRING
● EXPERIMENT MODULE	46.190	6.140
● CSM INTEGRATION	5.498	.394
● S-IVB MODIFICATION	.200	.050
TOTALS	51.888	6.584
TOTAL ONE FLIGHT	58.472	

ASSUMPTIONS:

- EXPERIMENT MODULE IS 12' CAN WITH SUBSYSTEMS.
- CSM COSTS ASSUME THAT FLIGHT IS AN ALTERNATE APOLLO FLIGHT.
- S-IVB MODIFICATIONS ARE FOR CABLE ATTACHMENT MECHANISM ONLY.
- NO EXPERIMENT COSTS ARE INCLUDED.

PROGRAM COST ESTIMATE

TABLE 11.1

MODIFICATION	NON-RECURRING	RECURRING
INTERNAL WIRE HARNESS WITH AUDIO HARDLINE	150K	70K
ECS CIRCULATION FAN WITH FAN AND DUCT IN CM TUNNEL	180	85
RCS JET DRIVER INTERFACE WITH THREE POSITION SWITCH FOR G&N, SCS, EXPT. MODULE	1500	100
DISPLAYS & CONTROL MODS	300	50
SLA FOLD BACK MODS	118	89
*CSM MISSION & SYSTEMS ENGINEERING INCLUDING CMC REPROGRAMMING	3250	--
TOTALS	5498	394

TOTAL ONE FLIGHT 5892

*ASSUMES ALTERNATE APOLLO FLIGHT

CSM MODIFICATION COSTS

TABLE 11.2

SYSTEM	MD-7			12' CAN		
	NR	R	TOTAL	NR	R	TOTAL
STRUCTURE	3.010	1.210	4.220	8.830	1.640	10.470
EPS	2.730	.720	3.450	2.730	.720	3.450
ECS	4.450	1.115	5.565	4.450	1.115	5.565
CREW SYS.	.700	.150	.850	.700	.150	.850
COMM.	5.680	.430	6.110	5.680	.430	6.110
INS.	.900	.230	1.130	.900	.230	1.130
SCS	9.000	.900	9.900	9.000	.900	9.900
SUBTOTAL	26.470	4.755	31.225	32.290	5.185	37.475
GSE	6.470	.240	6.710	8.000	.270	8.270
TOOLING	3.100	.225	3.325	3.840	.245	4.085
SYS. ENG.	1.670	.010	1.680	2.060	.010	2.070
SPARES	0	.390	.390	0	.430	.430
TOTAL	37.710	5.620	43.330	46.190	6.140	52.330

PROGRAM COST COMPARISON

TABLE 11.3

includes subsystem installation and integration, and the module level costs such as GSE, tooling, and systems engineering, which were estimated as a function of total subsystem costs. These costs are for the experiment module only and do not include any CSM integration or S-IVB costs.

11.4 Subsystems Costing

The subsystems costed in Table 11.4 are those described in Section 6 and are assumed to be the same for either configuration. In general, the estimates were based on ASTD, as well as other E&D division data.

11.4.1 EPS

The EPS is assumed to be similar to the AAP 1A system and used LM descent stage batteries. Included in the design cost is the cost of designing a new distribution system; however, the internal power umbilical from the CSM is costed with the CSM costs.

11.4.2 EC/LSS

The EC/LSS costs are based mainly on CSD costs which were generated in July 1967 for the MPTF second cluster exercises. The system components are in various stages of development under the SRT program at this time and the costs are considered realistic.

11.4.3 SCS

This system, one of the most expensive, utilizes one MSFC LM/ATM control moment gyro. The costs for the CMG and the Computer Control Electronics Assembly (CCEA) were obtained from MSFC, while the other SCS costs were estimated, based on ASTD historical data.

11.4.4 Communication and Instrumentation, Crew Systems

The costs for these systems have the least basis for historical estimating because they are not as close to past systems as some of the others. The communications system, of course, can be made very high or low, depending upon the assumptions to be made about data storage and return, experiment data, etc. The estimates are felt to be reasonable.

11.4.5 Structure

The detail on the structure estimates is included in Paragraph 11.5 and 11.6.

	D&D	FAB
EPS	2.730 M	.720
EC/LSS		
WASTE MANAGEMENT	2.500	.545
THERMAL CONTROL SYSTEM	1.210	.320
INSTRUMENTATION	.300	.500
METABOLIC	.440	.300
	4.450	1.115
CREW SYSTEMS	.700	.150
COMMUNICATIONS	5.680	.430
SCS	9.000	.900
CMG		.400
CCEA		.200
OTHER SCS		.300
	23.460	3.545

SUBSYSTEMS COSTING

TABLE 11.4

11.5 Structure Cost Estimates

11.5.1 Cable-Connected Vehicle

These costs were estimated, as illustrated in Table 11.5, for all the configurations. In general, the truss, subsystem support structure, experiment support structure and extension mechanism were assumed to be identical except for the SLA/Lab and the costs were estimated as a function of their weight (Fig. 11.1). The pressurized volumes were estimated as a function of volume and weight using an ASTD derived Cost Estimating Relationship (CER). This CER (Table 11.8) apparently gives a good comparison for relative costing. The structure design and development costs were estimated from other ASTD CER sources. In the cases where certain configurations could take advantage of current E&D work, such as the Subsystems Test Bed area, an appropriate amount of credit was given to these structures.

11.5.2 Moby Dick

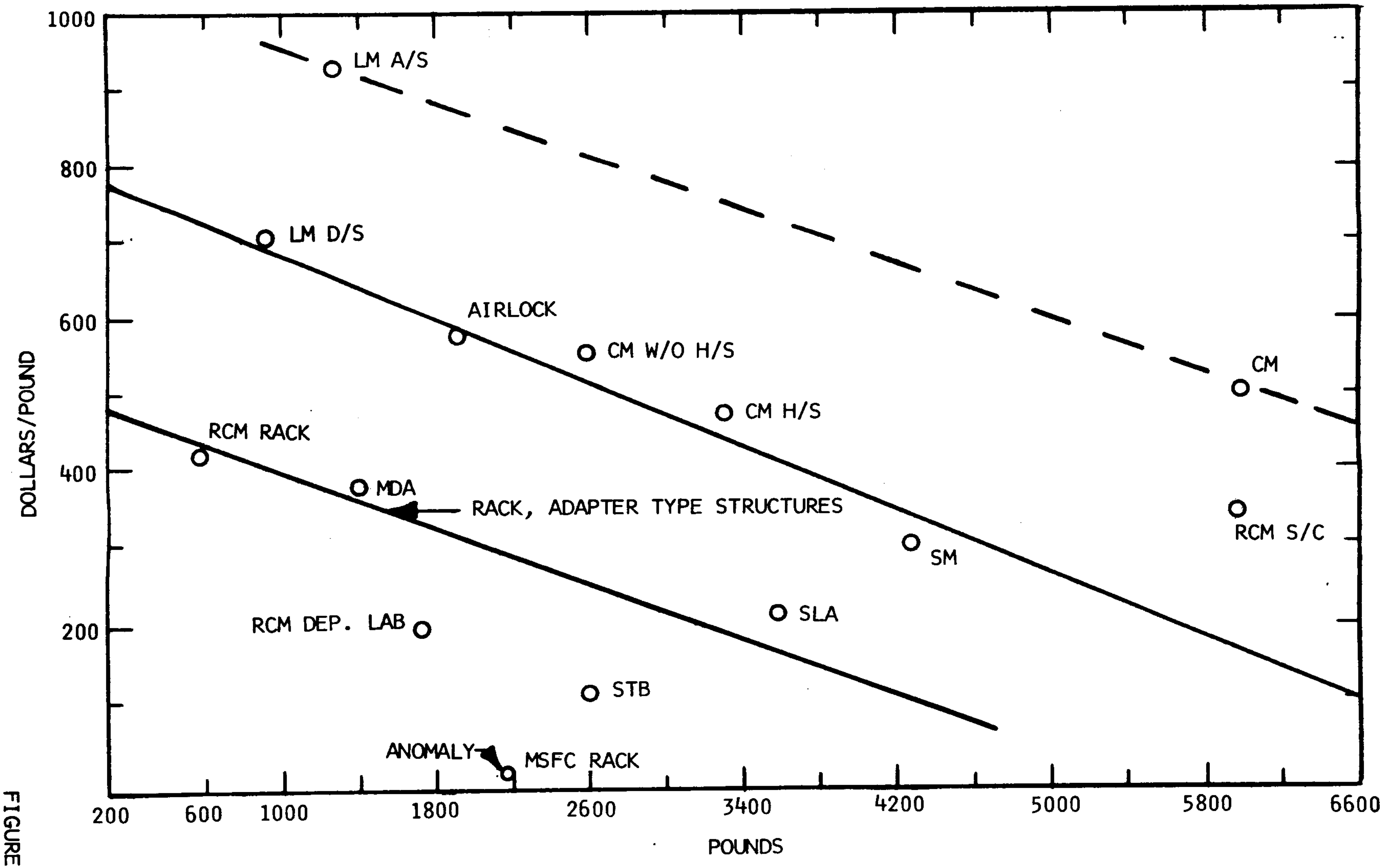
Table 11.6 shows that, similar to the cable-connected vehicle, much of the truss, docking structure and floors were assumed to be similar. Thus, the costs, estimated as a function of weight (see Fig. 11.1) were the same for these items. The expandable portion of the structure is explained in the following paragraph.

11.5.2.1 Expandable Structure Analysis

Quite a bit of data was available on expandable structure costs as Goodyear Aerospace Corporation (GAC) has built a prototype structure and Langley Research Center is in the process of testing it. The Moby Dick structure was assumed to be similar to this prototype; therefore, the GAC manhours have been used. However, this structure has not been tested for flammability and is a different size, so additional costs have been added for these two items. $1.\bar{0}$M is added for flammability testing and the LRC testing is assumed to be repeated, which should provide reasonable estimates. Table 11.7 indicates the costs estimates for the expandable structure.

11.6 Conclusions

The Moby Dick concept of achieving artificial "g" is felt to be the least expensive by $9.\bar{0}$M; however, other intangible considerations, such as crew safety, as well as the margin of error in the estimates, lead one to the conclusion, as has been indicated so often in the past, that to perform a certain mission under a fixed set of rules, the cost is the same, regardless of how the mission is accomplished.



RECURRING STRUCTURE COSTS
DOLLARS/POUND VS POUNDS

FIGURE 11.1

		PRELIMINARY COST ESTIMATES - STRUCTURES ONLY					
		10' CAN	12'CAN	12' CONE	ELLIPTICAL	SLA LAB	15' CAN
TRUSS	LBS.	400	400	400	400	0	400
	COST NR	1.800	1.800	1.800	1.800	0	1.800
	R	.190	.190	.190	.190	0	.190
SUBSYSTEM SUPPORT STRUCTURE	LBS.	284	284	284	284	284	284
	COST NR	1.420	1.420	1.420	1.420	1.420	1.420
	R	.220	.220	.220	.220	.220	.220
EXPERIMENT SUPPORT STRUCTURE	LBS	65	65	65	65	65	65
	COST NR	.490	.490	.490	.490	.490	.490
	R	.070	.070	.070	.070	.070	.070
EXTENSION MECHANISM	LBS.	430	430	430	430	435	430
	COST NR	.400	.400	.400	.400	.405	.400
	R	.200	.200	.200	.200	.205	.200
SUBTOTAL NON-RECURRING		4.110	4.110	4.110	4.110	2.315	4.110
RECURRING		.680	.680	.680	.680	.495	.495
PRESSUR-IZED STRUCTURE	LBS.	1800	2400	2300	2600	3600	3600
	VOLUME	655	942	842	969	2284	1250
	COST NR	3.400	4.720	6.440	7.020	9.000	6.000
	R	1.200	.960	1.030	.930	1.580	.660
TOTAL NON-RECURRING		7.510	8.830	10.550	12.130	11.315	10.110
RECURRING		1.400	1.640	1.710	1.610	2.075	1.155
TOTAL ONE FLIGHT		9.910	10.470	12.260	13.740	13.390	11.265

CABLE - CONNECTED VEHICLE

TABLE 11.5

		PRELIMINARY COST ESTIMATE - STRUCTURE ONLY			
		MD 1, 2, 4	MD - 3	MD - 5	MD - 7
TRUSS	LBS.	200	225	200	200
	COST NR	.110	.110	.110	.110
	R	.100	.100	.100	.100
DOCKING STRUCTURE	LBS.	100	0	100	100
	COST NR	.200	.200	.200	.200
	R	.060	.060	.060	.060
FLOORS	LBS.	550	0	550	550
	COST NR	.230	0	.230	.230
	R	.260		.260	.260
EXPENDABLE	LBS.	3370	3354	3354	1617
	COST NR	3.220	3.220	3.220	2.000
	R	.950	.950	.950	.500
WORK AREA STRUCTURE	LBS.	392	4710	392	392
	COST NR	.360	3.000	.360	.360
	R	.190	.600	.190	.190
DEPLOYMENT RESTRAINT	LBS.	198	198	198	198
	COST NR	.110	.110	.110	.110
	R	.100	.100	.100	.100
TOTAL NON-RECURRING		4.230	6.640	4.230	3.010
RECURRING		1.660	1.810	1.660	1.210
TOTAL ONE FLIGHT		5.890	8.450	5.890	4.220

MOBY DICK

TABLE 11.6

	MANHOURS			
ENGINEERING				
FABRIC	97,960			
SYSTEMS	4,710			
GSE	4,200			
MOCKUP	1,556			
DYNAMIC MODAL	2,156			
FLIGHT ARTICLE	6,040			
+ QUAL. ART.	18,172			
	134,794	HRS X $15/HR =	2.022 M	N-R
		+ LANGLEY COSTS	.200	
		+ FLAMMABILITY	1.000	
			3.222	
MANUFACTURING				
FABRIC	33,420			
GSE	6,113			
MOCKUP	1,014			
DYNAMIC MODAL	1,019			
FLIGHT ARTICLE	6,894			
+ QUAL. UNIT	6,894			
	55,354	HRS X $15/HR =	.830	
MATERIAL DOLLARS				
ENG.	40,000			
MFG.	80,900			
	$120,900		.121	
			.950 M	R

EXPANDABLE STRUCTURE ANALYSIS BASED ON GOODYEAR ESTIMATE

TABLE 11.7

DUE TO THE NEED TO COMPARE THE RELATIVE COSTS OF SEVERAL CANDIDATE STRUCTURES, THE FOLLOWING DATA WAS USED TO DERIVE A LEAST SQUARES LINEAR MULTIPLE CORRELATION FORMULA USING VOLUME AND WEIGHT AS THE INDEPENDENT VARIABLES. THE FORMULA IS VALID ONLY WITHIN THE BASE DATA RANGES AND CANNOT BE EXTRAPOLATED SINCE THE OBVIOUS CONCLUSION IS THAT IF THE WEIGHT AND VOLUME ARE LARGE ENOUGH, THE COST IS ZERO. HOWEVER, ALL THE CONFIGURATIONS BEING CONSIDERED FIT WITHIN THE REQUIRED LIMITS AND THUS THE RELATIVE COST ESTIMATES ARE FELT TO BE VALID.

FORMULA:

$$Z = 1.77 - .00064X - .000086Y$$

WHERE

Z = STRUCTURE RECURRING COSTS IN MILLIONS

X = PRESSURIZED VOLUME OF THE STRUCTURE IN FT^3.

Y = WEIGHT OF THE PRESSURIZED STRUCTURE IN LBS.

DATA*:

	X	Y	Z_a
MERCURY	110	420	1.66
GEMINI	200	1120	1.55
CM	380	2070	1.35
LM A/S	180	1370	1.54
STB	1220	5200	.54
A/L	300	1050	1.49
MDA	1350	3240	.63

*WEIGHTS AND VOLUMES FROM ASTD SPACE STATION DATA BOOK OF NOVEMBER 7, 1966.

DATA AND ESTIMATING BASE FOR RECURRING STRUCTURE COSTS

TABLE 11.8

CONCLUSIONS

1. Artificial gravity even at fractional "g" levels seems more efficient than zero gravity for crew work performance.

2. Artificial gravity systems costs can be offset by increased work efficiency. The additional manhours available for experimentation may pay for the additional cost of artificial gravity.

3. Subsystems requirements are similar for artificial "g" and zero "g" space stations with the apparent exception of the stabilization and control system; however, the system component differences are minor when accurate orientation is required for zero "g".

4. The subsystems hardware for the proposed mission exists and merely requires integration.

5. Modifications to the CSM and the S-IVB counterweight are minimum. Actually, most of the CSM modifications are required for the AAP flight 1A.

6. The single cable extension mechanism and associated dynamic control system are feasible, low cost, and compatible with the AAP.

RECOMMENDATIONS

The artificial gravity mission described in this study appears to be a low cost, low risk experiment that can be accomplished early in the space exploration program. Artificial gravity seems to be advantageous and convenient, and may indeed prove to be required for long-term space operations. For these reasons, the study team recommends that a deliberate effort be made to accomplish the delineated mission.

Further, if the mission bears out the conclusions derived from the study, subsequent planning of space exploration should incorporate the benefits of artificial gravity with the requirements for zero gravity.